25 years of MCDA in nuclear emergency management

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Abstract

Radiation accidents such as those at Three Mile Island, Chernobyl and more recently that at Fukushima have emphasised the need for supporting all phases of emergency management from the early phases in which a threat is detected to years and decades after the accident. Several decision aiding tools have been developed to prevent and mitigate the effects of a radiation accident. This work reviews a range of mathematical models, computing tools and, particularly, multi-criteria decision making techniques that have been applied in the last 25 years to help politicians, health officials, local authority representatives and emergency planning officers devise better countermeasure strategies in the event of a radiation accident. The paper discusses all phases of a nuclear emergency as well as emergency training and planning. It highlights what has been achieved in the application of multi-criteria decision analysis, mainly through initiatives such as the EU-funded 'RODOS' projects. It examines how such tools that have been developed fit into the formulation, evaluation and appraisal stages of the emergency management process and discusses the complex socio-technical issues that arise from radiation accidents.

Keywords: Multi-Criteria Decision Analysis (MCDA); crisis management; extreme events; decision support systems; nuclear and radiation emergency management; RODOS; stakeholder engagement.

Full citation:
Papamichail, K.N. and French, S., (2013), "25 Years of MCDA in nuclear emergency management" *IMA Journal of Management Mathematics*, Vol. 24, No. 4, pp. 481-503.
DOI: doi:10.1093/imaman/dps028

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1. Introduction

Twenty five years ago in 1986 the world's worst nuclear accident occurred at Chernobyl. It has been responsible, *inter alia,* for severe – but not perhaps as severe as sometimes perceived – contamination for tens of kilometres around the stricken reactor, for wide ranging debates on safety and viability of nuclear energy and for many developments since then in the emergency planning and management. In this paper, we explore several of these latter developments, particularly those related to decision support in emergency management and the use of multi-criteria decision analysis (MCDA). We shall note that the development of MCDA methods in this context occurred alongside some of the leading applications of stakeholder engagement and participation processes over the past two decades.

Our experience in this field began when at the turn of the 1990s one of us (SF) took part in the International Chernobyl Project (French *et al.*, 1992; French 1996; IAEA, 1991), specifically to explore the issues driving decision making on protective measures some four years after the 1986 accident. This work was one of the first real applications of MCDA to the context of a radiation accident and also provided an early example of the use of stakeholder workshops – though in those days we called them decision conferences. Over the intervening years, we have worked on the development of MCDA tools and on developing RODOS, a comprehensive decision support system for managing nuclear emergencies (Bartzis *et al.*, 2000; Papamichail & French, 2000; Geldermann *et al.*, 2009). We have also used many stakeholder workshops to identify a range of perspectives on appropriate guidance for recovery after a radiation accident. In doing so we have become part of a European community of academics, researchers, emergency managers, public administrators and others concerned with nuclear emergency management. This group is now embodied in the NERIS network (www.eu-neris.org).

In this paper, we reflect on these activities, on what we have learnt about using MCDA in nuclear emergency management and how MCDA can support stakeholder engagement in this context. In the next section, we describe, with considerable brevity, some of the history of MCDA and stakeholder workshops in nuclear emergency management and planning to set the context for our review. In Section 3 we briefly survey current thinking on emergency management, in particular nuclear emergency management; then in Section 4, we survey relevant MCDA methods, applications and processes. The following three sections cover, respectively, the formulation, evaluation and appraisal of MCDA problems in nuclear emergency management. In Section 8 we note that in many respects nuclear emergency management has been at the forefront of stakeholder engagement and public participation and that MCDA has helped structure these processes. We draw all the issues and themes of the earlier sections together in Section 9, discussing a range of previous papers. We next note that Fukushima has changed our perceptions further in that the impact of the radiation accident there is dwarfed by the other consequences of the Tsunami. Finally, we offer some concluding remarks. Our review avoids mathematical details in order to survey an exceedingly large literature on the modelling used in nuclear emergency management. Those mathematical details may be found via our citations. We conclude with some thoughts about future directions.

2. 25 years since Chernobyl

The Chernobyl Accident was in many ways an iconic event in human history. It changed many things; and among these it changed our approach to the analyses that support emergency management and recovery. One of us (SF) became involved in the recovery process in 1990 when he was invited to join the *International Chernobyl Project* as part of the team to investigate the decision making processes that had occurred since the Accident. This study had three primary objectives:

- to enable some of the decision problems related to the Chernobyl accident to be structured efficiently and thus clarify and elucidate issues;
- to summarise for the International Chernobyl Project the key socio-economic and political factors that together with the physical, radiological and medical evidence influence the relocation and protective measures taken in the Republics;
- to illustrate the use and potential benefits of formal decision analysis methods and the techniques of decision conferencing for the resolution of complex issues.

The first two are self-explanatory and clearly related to understanding the decision making underlying the recovery process. The third is important for this paper. It had been becoming clear that the then conventional cost-benefit analysis (CBA) to decision making in relation to radiation protection was inadequate to handle the complex issues that were arising in the Chernobyl region. Essentially the project was asked not just to investigate issues directly related to the Accident but also whether MCDA could offer the radiation protection and emergency management communities more support. Without delving into details the project did manage to use MCDA to elucidate the factors driving decision making post Chernobyl. Full details may be found in French *et al* (1992), French *et al* (2009) and IAEA (1991).

The study organised five decision conferences: one for each of the three republics – Ukraine, Belorus, and the Russian Federation – that were affected, one at all-Union level, and a summary one drawing participants from the first four together. The MCDA in the final conference was articulated on the criteria tree shown in Fig. 1.

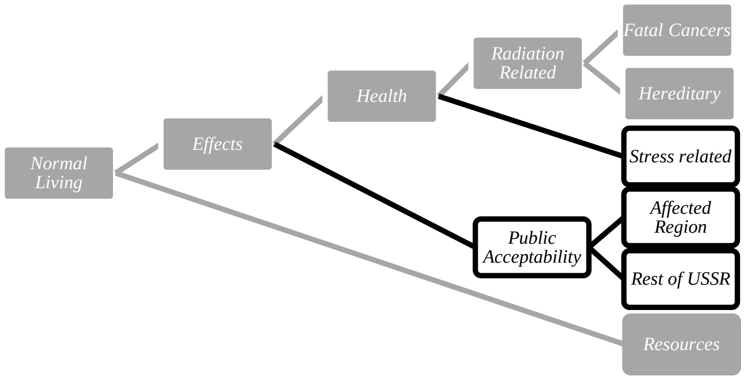

FIG. 1: The criteria hierarchy used in the International Chernobyl Project

Cost-benefit analysis as previously conceived for radiation protection decisions would only have considered the criteria indicated by solid grey parts of the attributes. It would have traded off *Radiation Related Health Effects* with the *Resources* needed to address them. The MCDA analysis showed clearly that the decision makers perceived (i) that there were significant health effects due to stress related to the accident and (ii) that the political acceptability of the recovery policies was important. The study achieved the third objective set to it, showing the value of MCDA over cost-benefit analysis. It is also interesting to note that the importance of stress in relation to health was elicited very clearly from the participants at all five conferences. Each was attended by frontline medical staff, experts from the various academies of science and medicine, and public and government officials. All were clear on the impact that stress was having on the affected populations, an impact comparable with that that might arise directly from the radiation. This has been subsequently confirmed by various medical studies and surveys (see, e.g., UNSCEAR, 2011). Many critics of MCDA and similar approaches decry judgement as unscientific and subjective, denying it a place in emergency management and recovery (as well as other contexts), but here we have a practical demonstration of the potential value of judgement in the period before full scientific evidence can be obtained, but nonetheless when major decisions have to be taken.

Catalysed by the results of this work and by its growing acceptance in other domains, MCDA has supplanted CBA to become the main approach to supporting decision making on recovery after a major radiation accident. We shall see below how it has been built into the main decision support tools.

During the 1990s there were many developments in decision support for nuclear emergency management driven by the findings from the International Chernobyl Project, key among which was the importance of a coherent, harmonised and sensitive response to nuclear emergencies. It was recognised that inconsistent responses from a variety of decision making bodies, regional, national and international – even if each is individually rational – confuse the public, leads to poor or ineffective implementation of countermeasures and raises the stress levels in the population, which, as the project had identified, can cause health effects and increased morbidity. In Europe it was argued that a mechanism for achieving broad consistency of approach would be the development and widespread installation of a common, comprehensive decision support system (DSS) for off-site emergency management. Two projects arose to build such DSS: a family of projects to build the RODOS DSS funded by the EU Framework Programme and a Danish initiative to build the ARGOS DSS. Over the past twenty years RODOS (Real time Online DecisiOn Support[1]) has been developed by a consortium of numerous EU, Eastern European, Russian, Belorussian and Ukrainian Institutes and it is now fully installed in several European countries. Further details of these projects may be found at the following web-sites: www.rodos.fzk.de/rodos.html, www.euranos.fzk.de/, and www.pdc.dk/Argos/decision.asp.

The functionality provided by such DSS tools varies, but generally they provide:

[1] An alternative acronym suggested by Simon French and Jim Smith based on Programmed Analysis of Nuclear Incidents and Countermeasures was rejected!

- forecasting and consequence models which predict the evolution and impact of the accidental release, including the scale and characteristics of the release, atmospheric dispersion and deposition, hydrological transport, food chain transfer, health effects and economic impacts;
- countermeasure models which predict the effect of applying given countermeasures, either individually or in a portfolio, in terms of human and animal health, agriculture, the environment and the economy (including costs) against a backdrop of the current best predictions of how the accident is evolving;
- evaluation tools, typically MCDA, for the later phases of the accident to support broad decision making on recovery strategies.

In addition, the DSS may include specific tools for setting up and exploring scenarios for emergency planning and exercises. For further information on RODOS and its development, see Ehrhardt *et al.* (1997), Ehrhardt and Weiss (2000), Bartzis *et al.* (2000), and the special issue of *Radioprotection* **45**(5). Over the years the ARGOS and RODOS systems have converged and are currently distinguished more by the supporting platform (MS Windows versus Linux) than functionality. Outside Europe other DSS have been developed though seldom with an intention of providing such comprehensive support: see French *et al.* (2007).

One area in which DSS tools for nuclear emergencies have lacked behind those in other domains is in their support for collaboration. In a crisis, a large number of individuals and groups have to work together. It is important to acknowledge that these stakeholders may not have worked together before. Therefore, we ought to design collaborative technologies taking into account individual and group issues (Turoff *et al*., 2011). To date, there are few features that explicitly support collaboration built into RODOS or ARGOS. Any such support has come from human facilitators involved in the process.

Alongside the development of DSS tools, planning for and the recovery from nuclear emergencies has looked more and more to stakeholder involvement and, to some extent, public participation. Indeed, it can be argued that this work has been at the forefront of developing means of engaging stakeholders and the public in deliberations. The Chernobyl decision conferences involved a wide range of stakeholders, albeit ones within the 'establishment'. The ETHOS project (Heriard Dubreuil *et al.*, 1999) used true and full public participation within a community to decide upon recovery strategies. The recent recovery handbooks (Nisbet *et al.*, 2010) were produced through a full and wide stakeholder engagement process. Moreover, post-Chernobyl studies (e.g. Drottz-Sjöberg & Sjöberg, 1990) have done much to stimulate the development of caring risk communication to ensure that the public is informed as sensitively as possible about the ongoing risks and underlying situation so that they face the future with realistic expectations (see, e.g., Bennett *et al.*, 2010). Generally the processes of emergency management and recovery have also been studied across Europe with a view to ensuring coherence between them (see, e.g., Carter & French, 2006). The European Platform NERIS (www.eu-neris.net) has been established recently as a forum for researchers, emergency managers, communities, operators, etc. It is hoped that NERIS will ensure that the coherence of approach that has developed across Europe since the Chernobyl Accident develops further, better assuring us of appropriate, effective and sensitive responses to any future radiation accident.

Thus while in this paper we discuss the role of MCDA in nuclear emergency management, it should be clear that our views have been developed in a much wider context.

3. Nuclear emergency management

A crisis is a high-impact, low-probability event. As Paraskevas (2006) points out, the word 'crisis' originates from the Greek word 'krisis' which means judgment, choice, decision. The main elements of a crisis are: ambiguity, high stakes, perceived urgency, rarity and significance of the event, and the level of impact on stakeholders (James *et al.*, 2011). It goes almost without saying that crises come in many forms: terrorist incidents, crowd disasters, oil spills, major fires, industrial accidents, epidemics and pandemics, droughts and famines, and seldom a news broadcast goes by without some economic crisis (Rosenthal and Kouzmin, 1997). Some crises are simply natural disasters beyond human control; others are the direct result of a failure of some human designed system.

Crises tend to evolve through a number of phases:

- *Planning Phase*. Before any crisis is apparent, any society or organisation should have an emergency planning function that 'scans the horizon' to anticipate potential issues that may impact upon them. Emergency planning is but one form of risk management in which threats are identified, assessed and plans laid for mitigating them (see, e.g., Aven, 2003). Generally in this phase, there are many imagined threats, all possible, but the vast majority, thankfully, very unlikely to occur. Away from the emergency planning function, society and the organisation goes on about their normal business.
- *Threat Phase*. Sometimes though a specific threat does become real and imminent with a significant probability of occurring. In this phase, society or the organisation considers whether to deploy a range

of precautionary measures anticipated in the emergency planning. Some will be adopted without thought, e.g. in the case of a malfunctioning plant or system there will be planned procedures for shutting it down and repairing the function. Others will require fine judgement about whether to implement them; e.g., when and how to warn those who may be affected and what measures to take to protect them: shelter or evacuate?

- *Response Phase*. Despite all efforts, the crisis may come to pass and then full emergency response will swing into action following well-rehearsed plans. Sometimes these plans will be precise and complete; other times, a portfolio of sub-plans will need knitting together, but the decision making and processes for doing this should have been well rehearsed in exercises during the emergency planning phase.
- *Recovery Phase*. Once the crisis is under control, there is a need to manage the recovery. It is seldom that the world can return to its previous state entirely. Perhaps the site, region or environment is damaged beyond repair. Even when the system can be physically rebuilt as it was previously, those involved, their communities and the organisation will have the memory of the incident with them for a long time. Managing realistic expectations of what will happen during the recovery phase is far more important than often thought. The stress impacts of the Chernobyl Accident arose partly though poor information and expectation management.

General discussions of crises, issues in managing the resulting emergency and then developing and implementing recovery strategies may be found in, e.g., Comfort (2005), Mitroff *et al*. (1996), Pearson & Mitroff (1993), and Pearson & Clair (1998). Over the years, the complexity of managing such events has increased which makes it difficult for those individuals and groups who are involved in the emergency management process to identify possible countermeasures and make effective decisions (Carver and Turoff, 2007). Thus, many emergency management information systems (EMIS) have been developed to help manage specific forms of crises. RODOS and ARGOS, mentioned above, are examples from the nuclear domain. For reviews and discussions of other EMIS, see, e.g., Van de Walle & Turoff (2007), and Van de Walle *et al.* (2009). The web-site of the International Community on Information Systems for Crisis Response and Management (www.iscram.org) is also very informative.

4. MCDA methods, processes and applications

Multiple Criteria Decision Analysis (MCDA) is "an umbrella term to describe a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter" (Belton & Stewart, 2002). Other terms, roughly synonymous with MCDA, abound. Many decision analysts talk of multi-attribute decision making (MADM) or, more specifically, the use of multi-attribute value and utility functions (French *et al.*, 2009; Keeney & Raiffa, 1993). Others refer to Multiple Criteria Decision Making (MCDM) (Köksalan *et al*., 2011). Stemming from the seminal work of Bernard Roy (1985), there is the French School who talk of Multi-Criteria Decision Aid (MCDAid) (see, also, Belton & Stewart, 2002; Perny & Tsoukiàs, 1996; Roy & Vanderpooten, 1996). Although each of the schools associated with these terms would argue that their methods are more specific or sophisticated in this way or that, there is a substantial overlap between them all in spirit and approach; and we shall ride roughshod over boundaries that others might respect.

Over the years there have been several state-of-the-art reviews and discussions of all these methods. In addition to those above, we also cite: Bana e Costa (1990), Clímaco (1997), Ehrgott *et al*. (2010), Figueira *et al.* (2005), Gál *et al.* (1999), Pardalos *et al.* (1995), Vincke (1992) and Zopounidis & Pardalos (2010). There is a wide range of MCDA applications ranging from competitive bidding (Liu *et al.*, 2000) to outsourcing maintenance (de Mello Brito *et al.*, 2010). Bibliometric analyses of the main fields, publications and authors are given in Bragge *et al*. (2010) and Wallenius *et al.* (2008). Earlier discussions of MCDA applications in nuclear emergency management can be found in French (1996), Hämäläinen *et al*. (2000), Sinkko (2004) and Andrews *et al.* (2008): the first three consider approaches based upon multi-attribute value theory; the fourth approaches based upon AHP. Recent wok on smart cities discusses the use of MCDA methods to evacuate people from a stadium, control traffic lights (Calabrese, 2011) and direct people to emergency exits (Moskvitch, 2011).

Even though MCDA models have typically been used for the evaluation of alternatives, they can also be used to reduce the complexity of a decision problem, generate creative alternatives, critique proposed plans, justify a decision, facilitate communication amongst stakeholders and increase confidence in evaluation results (Kasanen *et al*., 2000). More precisely, MCDA helps decision makers replace a complex decision problem with simpler ones (Keeney & Raiffa, 1976); evaluate alternatives using formal methodologies (von Winterfeldt & Edwards, 1986); think about values and value trade-offs in a systematic way (Keeney, 1992); cope with uncertainty and multiple objectives (von Winterfeldt & Edwards, 1986); and gain insight into the decision problem at hand by exploring it thoroughly through appropriate presentation of information and extensive discussion (Belton, 1990).

Decision analysis is not without its critics. The practice of MCDA is often seen as the formal representation of a decision problem and the mathematical techniques of solving it. MCDA methodologies lack any mechanisms for eliciting decision parameters from a decision maker without the presence of a decision analyst. As von Winterfeldt & Edwards (1986) note, while this enables the decision analyst to test the rationality of the decision maker, it is time-consuming and raises some intellectual and even ethical questions. Being engaged in a decision aiding interaction with a decision analyst is not a natural setting, but rather a matter of choice (Tsoukiàs, 2007). Decision analytic methods have also been criticised because it is difficult for those not versed in the theory to understand the validity of – and therefore adopt – the recommendations. Holtzman (1989) argues that it is unreasonable to assume that the decision maker(s) will allocate valuable resources for the implementation of an action merely because of the logical argument of a decision methodology. This leads to a less mechanistic, more process oriented view of decision analysis, one that is very sensitive to the underlying politics. This process perspective recognises that there is not just a need to determine the solution of a pre-defined decision problem; there is also a need to formulate the decision problem before the analysis and subsequently to interpret the results of the analysis into real implementation. We should view MCDA as a multi-stage process and provide support before and after the application of quantitative techniques that trade-off and balance conflicting scores on the criteria. This argument is particularly emphasised in French *et al.*(2009) where the use of MCDA is illustrated in complex societal decision problems.

We have defined a decision model 'as a formal representation of the decision problem that reflects a decision maker's real situation' (Papamichail & French, 2005). In order to help the decision makers gain insight into the decision problem and clarify their preferences guidance is given in three stages (Holtzman, 1989), see Fig. 2:

FIG. 2: The process of MCDA

- Formulation of the decision model i.e. identifying evaluation criteria and devising alternatives.
- Evaluation of the decision model i.e. calculating the consequences of the alternatives, establishing their implications, evaluating the alternatives using a formal MCDA method and producing a recommendation.
- Appraisal of the recommendation i.e. interpreting and justifying the recommendation.

It should be noted that this process is not sequential. A refinement/feedback loop implies that decision makers can iterate between stages. If they are uncomfortable with the recommendation, they can step back to revise the list of criteria, consider a larger number of alternatives and conduct another evaluation round. The decision model is progressively revised until the decision maker is confident that the structure, elements and values of the decision model accurately represent the decision problem. Philips (1982) argues that after several iterations, the final decision model is requisite: i.e. comprehensive enough to allow the decision makers to make a decision without considerable effort.

With this background, in the next three sections we step through the formulation, evaluation and appraisal stages of MCDA in the context of nuclear emergency management, drawing both on our experiences in the RODOS projects and on the literature.

5. Formulation of MCDM problems in nuclear emergency management

The formulation stage involves the identification of alternative countermeasures and evaluation criteria. There have been examples of combining problem structuring methods with MCDA to structure decision problems prior to the evaluation of alternatives (Belton & Stewart, 2010; French *et al.*, 2009). General discussions of problem formulation methods, often called soft modelling or soft OR methods, may be found in Franco *et al.* (2006, 2007). Note also that some developments in these general methods have been catalysed by the use of MCDA in nuclear emergency management: see, e.g., Comes *et al.* (2011) and French (2011). Whereas there has been a wide range of applications of these methods in the UK and Europe, their use is not as widespread in the US. As Paucar-Caceres (2011) points out there appears to be a divide in Operational Research/Management

Science between the US and the UK that can also be viewed as a divide between two communities: the Ms (Mathematicians) and the STs (Social Technologists).

In MCDA, the criteria (also called attributes) which can be used to assess alternative countermeasure strategies are structured in criteria trees or hierarchies. FIG. 1 provides an example from the Chernobyl study. In the threat and emergency phases of a nuclear crisis though, it is doubtful how much time the decision makers can devote to articulating their values and objectives. However, much work on these can be conducted during emergency planning, particularly during exercises which may be used to drive a systematic approach to generating alternatives. In our experience one of the benefits that MCDA has brought nuclear emergency planning is the explicit discussion of objectives during emergency planning. In the past there was a tendency to take the objectives as read and 'play the game' during the exercises simply to minimise one or two simplistic, usual implicit objectives. During the recovery phase, there is ample time to develop appropriate criteria trees. The recovery handbooks (Nisbet *et al*. 2010), among other things, provide guidance on this. There are several studies that illustrate attribute trees applied to nuclear emergency problems (Turcanu *et al*., 2008; Geldermann *et al*., 2009; Mustajoki *et al*., 2007; Papamichail & French, 2000). In almost all cases the criteria trees involve both 'objective' and 'subjective' criteria. Examples of the former are area contaminated above a given level, number of people evacuated, dose received by a community; examples of the latter are public acceptability, ethical integrity and cultural heritage. The former can be calculated by an EMIS such as RODOS for each strategy to be evaluated; the latter can only be assessed judgementally and require the emergency managers and possibly some of the stakeholders to agree on the values to be ascribed to each strategy.

RODOS and many other EMIS used in nuclear emergency management use forward simulation to forecast the spread of contamination and its impacts. This means that is difficult to request that impacts are calculated for specific criteria during the MCDA support deliberations on countermeasures. So RODOS essentially calculates *all* the objective criteria scores it can building an impacts database and then allows the MCDA module select the objective criteria that are important to the decision makers' deliberations in specific contexts.

Raskob (2010) lists countermeasures for different phases of a radiation accident such as evacuation, sheltering and decontamination of inhabited areas and discusses how to model to calculate their effectiveness. According to a set of guidelines devised by the International Atomic Energy Agency (IAEA, 1991), the formulation of countermeasure strategies should be driven by the following two considerations. Firstly, 'the proposed intervention should do more good than harm'. In some cases, the social costs combined with the harm caused by the intervention itself outweigh the benefit of reducing exposure to radiation which leads to an overall negative net benefit. Secondly, 'the form, scale and duration of the intervention should be optimised'. Maximising the overall net benefit should remain the primary objective. The principle of optimisation was further reinforced by ICRP recommendations (ICRP, 2007).

Radiation protection bodies such as IAEA and ICRP provide specific advice about courses of action after a radiation accident. They produce guidance to supplement any priori judgement. Taking into account all this advice, possible portfolios of countermeasures need be created during the different phases of a nuclear accident. In the threat or emergency phase, there is again little time to do this. Some preparation can be undertaken during the planning phase, but whereas values and objectives are to some degree generic and can be applied to any emergency, the possible countermeasures may be constrained by specifics of a particular emergency: e.g., by weather or traffic conditions. For this reason, the use of artificial intelligence and constraint management techniques have been suggested to identify specific countermeasures that should be considered during the threat and emergency phases (Papamichail & French, 2000).

The recognition of the importance of involving *all* stakeholders in emergency management and recovery has been driven in part by our experiences after Chernobyl. The stress and public acceptability criteria in FIG. 1 are an early indicator of this importance. Thus another important aspect of the formulation stage is the identification of stakeholders. Again this is too time-consuming a process to be conducted during the threat and emergency phases, but can be part of the preparations during the emergency planning phase and subsequently confirmed during the recovery phase. Stakeholders include individuals and groups who may be – or *believe* that they may be – impacted by the crisis (Marcus & Goodman, 1991; French *et al*., 2009). Broadly speaking, stakeholders are individuals, groups or organisations, including any powerless parties, which need to be taken into account (Bryson, 2004). They may include employees, consumers, communities, and those who care for the natural environment (Mitroff et al., 1996). In stakeholder theory, there is no divide between 'business' and 'ethics' (Drake *et al.*, 2011). Understanding the impact of stakeholder dynamics is central in the formulation of stakeholder engagement strategies (Ackermann & Eden, 2011). In nuclear emergency planning, it is essential to identify stakeholders and encourage the participation of the public in the formulation of risk assessment strategies (Boiko *et al.*, 1996; Drew *et al.*, 2003).

6. Evaluation of MCDM problems in nuclear emergency management

Once the criteria, also called attributes, have been articulated and the alternatives have been formulated, the next step is to evaluate the proposed alternatives. There are several MCDA approaches to assessing alternatives such as the value function approach, outranking methods, goal programming and the Analytic Hierarchy Process (AHP). We lean towards using the first of these in our applications. As Belton and Stewart (2002) point out they all focus on the structuring of the problem in terms of alternatives and criteria but they differ in the way that compromise between conflicting criteria is achieved. Value function approaches encourage the explicit articulation of tradeoffs between criteria. Outranking methods evaluate alternatives in pairs by identifying incompatibilities, indifferences and vetoes. Unlike other approaches, they assume that preferences and values are not pre-existing but should be constructed during the MCDA process. Goal programming is applied when it is difficult to articulate tradeoffs and importance weights but it is possible to express goals and aspirations for all criteria. AHP assesses alternatives in pairs using semantic scales such as 'highly important' rather than numerical scores.

In order to conduct a MCDA using Multi-Attribute Value Theory (MAVT), a value function needs to be constructed. The value function is used to represent the preferences of the decision makers in a convenient form for the evaluation of alternatives. If significant uncertainties are to be modelled probabilistically and thus if Multi-Attribute Utility Theory (MAUT) models may be needed, this value function may be seen as a first step to constructing a utility function (Keeney and Raiffa, 1993). Preferences can be represented in different forms depending on whether particular independence conditions in the criteria are satisfied.

The additive model gives the form of a simple weighted sum to the value function, but requires full preferential independence, a strong assumption (von Winterfeldt and Edwards, 1986; Keeney & Raiffa, 1993). Given attributes $X_1, ..., X_n$ ($n \geq 3$), let $\mathbf{x} = (x_1, x_2, ..., x_n)$ be the consequence of an alternative, where x_i ($1 \leq i \leq n$) is a score i.e. the level of this alternative on the i^{th} attribute/criterion. An additive value function takes the form:

$$\upsilon(\mathbf{x}) = \sum_{i=1}^{n} k_i \upsilon_i(x_i), \qquad 0 < k_i < 1$$

where $\upsilon_i(x_i)$ is a marginal value function over attribute X_i and the k_i are scaling factors (Keeney, 1980) that are also called weights. Such a form is valid if and only if the attributes $X_1, X_2, \ldots, X_n$ are perceived by all decision makers and stakeholders as being mutually preferentially independent: i.e. marginal values $\upsilon_i(x_i)$ on the i^{th} attribute do not depend on those on other attributes. This additive MAVT model, which is also known as a weighted sum model, has been recommended by the ICRP (1989). It is the most widely used MCDA approach (Triantaphyllou, 2000). In terms of publications though, AHP appears to be the most popular approach (Wallenius et al., 2009).

A utility function can take several forms under some well-defined conditions. The additive and the multiplicative forms are the most common ones:

$$u(\mathbf{x}) = \sum_{i=1}^{n} k_i u_i(x_i) \text{ or } u(\mathbf{x}) = \prod_{1}^{n} k(1 - k_i u_i(x_i)) \qquad , \qquad 0 < k_i < 1$$

where the $u_i(x_i)$ are marginal utility functions and the k, k_i are scaling constants (not necessarily the same in the two forms). Which of these forms (or any of the other less common) are appropriate is again determined by which dependence/independence conditions are perceived as appropriate by the decision makers' and stakeholders' preferences.

There are several nuclear related applications of MCDA methods. For example, in nuclear waste management cases AHP, MAUT and fuzzy sets have been applied to collect the views of members of the public and establish their risk perceptions (Sohn, 2001), PROMETHE has been used to rank geological repository sites (Briggs, 1990) and ORESTE has been applied to a nuclear waste management problem with limited available information (Delhaye et al, 1991). Roy & Bouyssou (1986) compare ELECTRE III and MAUT in a nuclear power plant siting application and Hämäläinen (2000) applies AHP to establish whether a nuclear plant should be constructed in Finland.

In the RODOS project, a MAVT-based system was developed to rank alternative countermeasure strategies (French, 1996; Papamichail & French, 2000). In subsequent EU-funded projects, the MAVT system was replaced by more established commercial packages with a wider range of functionalities, e.g. a range of methods for eliciting weights and facilities for drawing attribute trees (Mustonen, 2005). Web-HIPRE was used in the EVATECH project (Geldermann *et al*., 2008) and VISA in the Argos project (Hoe *et al*., 2009). Even though MAUT has been widely applied to nuclear-related applications in the US (see, e.g, Merkhofer & Keeney, 1987), it has never implemented in the EU-funded projects. Papamichail & French (2000) discussed the use of an exponential utility function, but the approach was not tested in any decision workshops nor training exercises. As Hämäläinen et al., (2000) remarked, the elicitation of risk attitudes and the construction of utility functions are rather problematic when dealing with decision makers who are not familiar with the techniques. Perhaps a more important reason is the difficulty of getting enough of a handle on all the uncertainties to build a sufficiently broad probability model that would be needed to partner the utility function to form expected utility rankings. Uncertainty is generally handled in MCDA through the use of sensitivity analysis in the exploration of the MCDA models.

7. Appraisal of MCDA problems in nuclear emergency management

In a radiation accident, various decision makers ranging from emergency planning officers and plant managers to politicians will be involved in the decision process. These decision makers may not have much expertise in the area of MCDA. They may perceive a MCDA tool or process as a black box where their values such as weights and scores are elicited and then the output of the analysis, that could be a ranked list of alternatives, is presented to them. Yet, these non-experts would be expected to interpret the results of the MCDA analysis, take a decision and commit to an action plan. They should also justify their decisions and ensure that their actions do more good than harm (ICRP, 2007).

Explanation facilities can improve the performance of both professionals and novices (Gregor and Benbasat, 1999; Mao and Benbasat, 2000). Longer explanations in particular, increase the likelihood of acceptance by the decision makers (Gönül *et al*., 2006). Early work in the area of expert systems has shown that the users of a system that dogmatically offers advice are very likely to reject it, even if the system provides reliable and accurate results (Teach and Shortliffe,1981). In order to establish trust in the results of a system, users would need to receive assurance that the system's reasoning is sound and appropriate (Swartout, 1983).

The MCDA tool that is part of the RODOS project has evolved over the years. The original ranking module (Papamichail & French, 2000) was replaced with Web HIPRE (Hämäläinen, 2003), a software tool that operates on the Web and provides facilities for eliciting values such as weights and scores. The explanation module however, which explains how the MCDA tool ranks alternatives, remains the same and it is now integrated with Web-HIPRE (Geldermann *et al.*, 2009).

The explanation module produces two reports:

- A comparative report that discusses how much better an alternative is over another, establishes the extent to which a criterion differentiates between two alternatives and identifies those criteria that are significant in the ranking of the alternatives.
- A sensitivity analysis report that analyses sensitivity analysis graphs and discusses the effect of changing the weight of an attribute on the ranking of the alternatives.

Sensitivity analysis is a useful tool that can generate valuable insights. As French *et al.* (2009) point out sensitivity analysis graphs can be used to explore the sensitivity of the output to different judgemental inputs (e.g. weights of criteria) and identify those that really matter. This is because, occasionally, the conclusions of the analysis remain unchanged even for substantial changes in inputs. Therefore sensitivity analysis can resolve conflicts within a group of decision makers by helping them concentrate on important issues that affect the final decision rather than spending unnecessary time and effort assigning precise values to input variables. In a workshop with stakeholders that was conducted in Germany, participants found the sensitivity analysis graphs as well as the comparative and sensitivity analysis reports to be particularly useful (Geldermann *et al.*, 2009).

The explanation module combines natural language generation methods (Reiter & Dale, 2000) with statistical techniques (Klein, 1994) to generate natural language explanations in any problem where a MAVT function has been applied to rank alternatives. Carenini & Moore (2006) follow a similar approach to build a system that generates arguments for and against a choice. They evaluate their tool by measuring the extent to which a user adopted the recommended alternative and her confidence in the results. Amgoud & Prade (2009) propose an argument-based framework for generating explanations in multi-criteria decision problems with uncertainty. Finally, recent research in the area of explanation systems seeks to generate explanations in cost-minimisation multi-criteria decision problems (Labreuche *et al*., 2011) and in Markov decision processes using case-based techniques (Dodson, *et al*., 2011).

8. Stakeholder involvement

Involving *all* stakeholders in the planning for, management of and recovery from a nuclear emergency is of paramount importance. Despite some cynical views, there is no doubt that radiation protection, other experts and the emergency managers are responsible people, who strive to protect the public (Roberts, 1984). Nonetheless, to build and maintain trust with the public, it is important to recognise the need for transparency of and, when possible, stakeholder involvement in the deliberations and decision making. This need for stakeholder involvement was recognised in the wide range of participants who took part in the Chernobyl decision conferences; though all who took part did so in some official capacity – there were no public involved. During the 1990's, as moves towards more stakeholder and public engagement in all areas of societal decision making began (see, e.g., Bayley, 2008; Gregory *et* al., 2005; Renn, 2008), so a wider range of stakeholders became involved in nuclear emergency management (see, e.g., Sinkko, 2004). The ETHOS project on recovery and the adoption of lifestyles that mediated risks from post-Chernobyl contamination in Belorus involved all members of a village (Herriard Dubreuil *et al*., 1999). Several projects related to RODOS, but particularly the EVATECH project (Mustonen, 2005) ran workshops with various stakeholders in which nuclear accidents were simulated and the imperatives driving decision making during recovery were explored using a variety of MCDA tools (Niculae, 2005). As in other domains, this use of MCDA showed that it helps deliberations in separating facts and predictions from values, enables appropriate inputs from scientists, experts and stakeholders to the process and facilitates communication between all parties (Morton *et al.*, 2009). Thus, for over twenty years, the nuclear emergency management has led in many of the developments in stakeholder engagement and public participations.

Radiation accidents are thankfully rare so most of the work on MCDA and stakeholder involvement if focused on planning for the management of and recovery from such events. When devising plans, it is not possible to predict all possible scenarios. The emphasis, therefore, is not so much on deciding on what to do in an accident, but on establishing a well-defined decision process in advance, establishing which stakeholders to involve in the management and when and, above all, sensitising all parties to the issues to consider and the values to drive decision making (Turoff *et al*., 2010). To date, there has been less sign of stakeholder fatigue than in other domains and it has been possible to recruit broadly representative groups of stakeholders to help in this. A recent survey in Belgium identified population segments that were more or less likely to engage in participatory decision making exercises (e.g. focus groups, citizens' juries, decision workshops) regarding nuclear plant installations (Turcanu & Perko, 2011). Men, members of large families, those who self-assess themselves as cautious, those with scientific interests and those lacking trust in the authorities were more willing to participate actively. Women, those on low-incomes or with high chemical/nuclear accident risk perceptions were less likely to contribute their time.

Even when stakeholders are involved, public policy deliberative processes often lack clear direction. As Gregory *et al*. (2005) explain, when devising health and environmental policies, stakeholder groups such as community members, technical experts and policy makers distrust each other and therefore undermine the process. It has been argued that MCDA can be used to guide and facilitate procedures in nuclear-related deliberative processes (Morton *et al*., 2009). Findings in the area of behavioural decision research could also be particularly useful in devising for example communication strategies (Gregory *et al*., 2005).

9. Discussion

In recent years, the rise in oil prices combined with concerns about increasing levels of CO_2 emissions has shifted attention back to nuclear power as a viable or alternative energy source (Mazen, 2009). Uncertainty over climate change and gas supplies has made governments consider the continuity of nuclear reactor programmes (Cox, 2007). Emergency planning for nuclear power plant and nuclear fuel cycle incidents will remain a necessity for years to come.

MCDA has shown its worth in emergency planning for nuclear accidents; and we believe that in the event of a future accident it will show its worth in managing the response, at least in the later phases, and recovery. Above, we have cited much work to support these statements. In Table 1 we consider a number of papers in more detail, identifying the benefits brought to the emergency management process by MCDA. Two points should be noted. Firstly, MCDA is clearly seen as more relevant to the response and recovery phases of an accident. Only one paper (French & Papamichail, 2005) considers its use in the threat and early part of the response phase and in that case we did not foresee a full application of the MCDA process. Rather a semi-automated process is applied with the emergency managers able to explore the effect of minor modifications to the value structure on the recommended portfolio of actions. Secondly, the absence of any support for the planning phase in Table 1 is more apparent than real. As we noted above the planning phase is usually driven by learning from exercises and MCDA can and has been applied in these to consider many parts of planning for the response and recovery phases.

The support for deliberations between stakeholders and building a shared understanding of the issues and possibly consensus is also clear from all the papers. MCDA is as much about communication as decision making. Several of the papers emphasise the manner in which MCDA structures the decision making process, bringing consideration of the various issues in a logical fashion. The ability to draw together tangible and non-tangible factors – objective and subjective attributes – is also noted in several of the papers.

Table 1: Benefits of MCDA in nuclear emergency management

Emergency phase	Benefits	Citation
Threat and Response	• identify alternatives in different nuclear accident scenarios • explore the effect of changing the values of decision parameters in the ranking of the strategies • consider factors such as social effects that are difficult to grasp • practice how to take decisions under different circumstances	Papamichail & French (2005)
Response and Recovery	• identify new solutions and explore efficient alternatives • facilitate cooperation between stakeholders	Perny & Vanderpooten (1998)
Response and Recovery	• follow the decision analysis process in a structured, systematic, logical and efficient way • think about values and identify those factors that have an impact on the decision	Hämäläinen *et al.*, (2000)
Response and Recovery	• plan later phase alternatives • understand the views of other stakeholders • help the participants to prepare for a real accident situation • set up a network of key players in nuclear emergency management	Mustajoki *et al.*, (2007)
Response and Recovery	• ensure the transparency of the decisions taken • understand the opinions and views of other participants • support, structure and document decision processes • apply it to training exercises	Geldermann *et al.*, (2009)
Response and Recovery	• overcome the limitations of other methods such as Cost-Benefit Analysis particularly when considering non-monetary and intangible issues (e.g. environmental, social, cultural or psychological aspects) • enhance the quality of the decision-making process • promote discussions and interactions amongst decision makers and stakeholders • reach a common understanding of the decision problem	Turcanu *et al.* (2008)
Response and Recovery	• achieve 'differentiated consensus' i.e. 'consensus on basic truths' with 'remaining differences' (i.e. differences remain but they are not regarded as dividing)	Mercat-Rommens *et al.* (2012)

10. Reflections after Fukushima

This year's dreadful earthquake and tsunami in Japan and resulting radiation accident at Fukushima raise obvious questions about whether the learning from Chernobyl and subsequent developments discussed above have helped the authorities respond to the crisis. Although a range of reports are coming out at the moment (see www.iaea.org for several links), it is too early to say much with any authority – the reactors have only just been declared stable. Early countermeasures such as evacuation and the issuing and uptake of stable iodine tablets were implemented more quickly and effectively. However, on some of the key issues such as information management and public communication, the picture is not so clear and will need much analysis. There are indications that the authorities have not been as open with the public about the situation nor made them partners in handling it. One area in which the DSS systems that we have referred to above clearly 'failed' was in some of the fundamental modelling. Atmospheric and hydrological dispersion models built since Chernobyl have broadly assumed that the accidental release of radiation is short lived; that after a few hours, at most a few days, the leak will be sealed. They are not applicable to chronic low level releases which continue for weeks, as they have at Fukushima. The common view in emergency management that we always prepare for past crises not future ones has never been more true.

The other issue that Fukushima has bought to the fore is that in planning for radiation accidents it has generally been assumed that the leak of radiation into the environment was the worst to happen. But in the case of Fukushima the Tsunami was a far more serious event, destroying communities and infrastructure, and causing a dreadful death toll. The issues that arise from that dwarf the response and recovery from Fukushima alone, and the processes will necessarily be hugely different. Many researchers ascertain the need to develop 'high-reliability' organisations (Weick & Sutcliffe, 2007) that will withstand the ferocity of natural and man-made disasters. For example, Lindell & Perry (1997) have emphasised the need to assess the risks of earthquakes on hazardous material sites. However, it is manifestly very difficult to establish what a worst case scenario may entail and subsequently develop defence mechanisms against such disasters.

In the event of occurrence of a radiation accident, subsequent studies seek to establish the causality effect (i.e. what caused the event) and any 'lessons learned'. But in doing so they often focus on the specifics of the incident, rather than step back far enough and identify much broader lessons. When a similar incident takes place however, it becomes apparent that 'the similarity' is not sufficient for the lessons learned to be applied without modification or, perhaps worse, they have not been learned sufficiently to be applied. As Denyer & Kelliher (2011) point out, the emphasis on establishing the events that led to the previous incident may lead to over-detailed changes in emergency planning rather than an introduction of sensitive flexibility into processes to enable them to respond better to unfolding events. We believe that MCDA provides a sensitive and flexible structure in which to think about potential events and, should the need occur, respond and recover from these. It does not constrain one to specific details of previous events. As Perry & Lindell (2003) note, training is central to emergency planning. Thus we believe strongly that we should train emergency planners and managers in MCDA so that they can embrace the methodology.

Acknowledgements

The authors would like to thank Emma Carter, Jutta Geldermann, Joachim Ehrhardt, Neale Kelly, Jacques Lochard, Carmen Niculae, David Ranyard, Jim Smith, Theo Stewart and all their colleagues from European projects extending from the earliest 'RODOS' project to the current NERIS network/platform (www.eu-neris.net) for all their constructive discussions over the years. We have been funded from several EU framework programmes.

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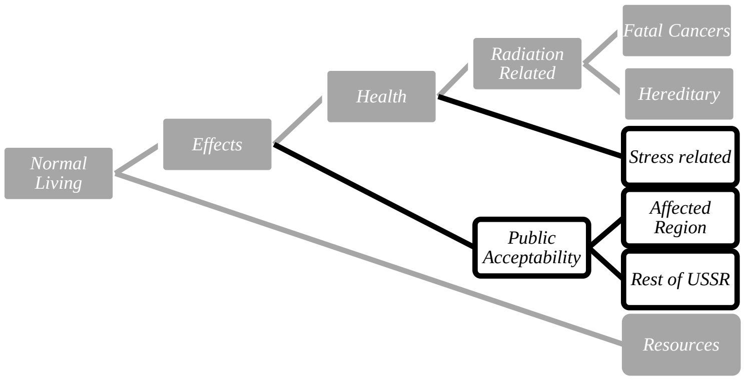

FIG. 1: The criteria hierarchy used in the International Chernobyl Project

FIG. 2: The process of MCDA