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A Framework for Evaluating Emergency Preparedness Plans and Response Strategies

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Foreword

Development of preparedness plans and response strategies is an important element of emergency management. Although there are diversified guidelines for, and experience with development of such plans there has been no comprehensive framework for their evaluations. The research reported in this paper aims at filling this gap.

The author proposes a framework for evaluating emergency preparedness plans aimed at plans requiring multi-agency cooperation and coordination, and illustrate the framework applicability to the actual plans implemented in European Nordic countries. The proposed evaluation criteria result from the analysis of findings in social science research on emergency management. The decision evaluation is a clearly multi-criteria problem. To effectively address it a new method for multi-attribute decision evaluation is proposed.

The results described in this report were achieved during the IIASA 2007 Young Scientists Summer Program. The author was awarded with the *Honorable Mention* citation for the quality of his research that can characterized by a quotation from a review:

> *"The problem the author is addressing in the paper is very complex. He has approached this problem with decision analysis tools aimed at helping to structure the problem for decision making"*.

Abstract

A framework for evaluating emergency preparedness plans is presented, aimed at preparedness plans requiring multi-agency cooperation and coordination. The approach relies on an evaluation by criteria, assessing degrees of fulfillment for criteria which are collected from findings in social science research on emergency management. The criteria are categorised into 1) organisational criteria, 2) maturity criteria, and 3) effectiveness criteria. The first category is concerned with properties of the ad-hoc organisation set-up, having nodes in several different agencies. The second category assess the technical and non-technical, activities or solutions planned or implemented and their stage of development. The third category is concerned with a knowledge of response effectiveness, using numerical metrics to measure effectiveness and consequences.

Further, a new method for multi-attribute decision evaluation of different response strategies is suggested. The method allows for soft input relaxing the requirement for specifying precise trade-offs between a set of reasonable attributes. This method can be used as a complement to cost-benefit analyses in the evaluation and selection of cost effective and reasonable response strategies.

Acknowledgments

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About the Author

Aron Larsson graduated from Mid Sweden University in 2004 with an M. Sc. in Computer Engineering and a Master's degree in Business Administration.

His main field of scientific interest is the development of a decision analytical framework supporting imprecise and vague input statements. His work includes conceptualization, implementation and applications of decision analysis techniques on real-life problems.

Since January 2004 he is a member of the Risk and Decision Analysis Lab. at the Department of Information Technology and Media of Mid Sweden University, where he works as a Ph. D. student. In 2007 he joined the Integrated Modeling Environment Program as a Participant in the Young Scientists Summer Program.

He received from IIASA in 2008 an "Honorable Mention" for his research on *A Framework for Evaluating Emergency Preparedness Plans and Response Strategies*.

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A Framework for Evaluating Emergency Preparedness Plans and Response Strategies

Aron Larsson (aron.larsson@miun.se)[*]

1 Introduction

Any spatial-temporal event leading to an emergency situation for affected regions and their citizens calls for a response by authorities in order to mitigate the effects of the event. Several authorities and agencies, holding different expertise, must cooperate to cover the necessary aspects and base the response upon well-informed decisions. To cope with this, preparedness plans, outlining the structure of an ad-hoc organisation, is set up with units in the different agencies. The interactions and responsibilities of the agencies should be as pre-defined as possible for the response process and related activities to run as efficient as possible. Thus, the underlying assumption is that the effectiveness of the response relies partly on the quality of the preparedness plan, cf. McLoughlin 1985; Levine 1989; Lindell 2000; IAEA 2002.

It is common to partition emergency management activities in four different categories, often undertaken in a temporal order: (1) *mitigation*, (2) *preparedness*, (3) *response*, and (4) *recovery*, see, e.g., Petak 1985. Activities falling into the *preparedness* category include; construction of warning systems, construction of emergency operations plans, establish emergency operations centres, defining intra- and inter-organisational communication patterns as well as communication to the public. In contrast, activities falling into the category of *response* include; activation of emergency plans and systems, sending out emergency instructions to the public, manning emergency operations centres, shelter, evacuation, search and rescue, cf. McLoughlin 1985.

A preparedness plan may be seen upon as a result of contingency planning, i.e., planning against unexpected, undesired, but nevertheless reasonable scenarios. In this respect, one single preparedness plan is usually aimed to be executed against a particular element of threat. For instance, a preparedness plan against a flood emergency will not be identical to a plan against a nuclear emergency, still, different plans share some approaches and components.

Although a preparedness plan is a collection of guidelines, regulations, and choice rules, it is of equal importance an organisational scheme with distributions of tasks and responsibilities to be carried out and held by the agencies engaged. As Perry and Lindell [2003] states: "[the plan] defines the organisational structures by which a coordinated response is to be made".

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Evaluation of preparedness plans is important in order to identify strengths and weaknesses in different approaches as well as an aid in documenting improvements (or deteriorations) made over time. In particular, for authorities or agencies responsible for the monitoring, evaluating, and aiding in design of national or regional/local preparedness plans with respect to different events, structured methods for evaluating such plans may be of great value. This applies to both when comparing between different practices and between newer and older plans, as the documented plan may be seen upon as a snapshot of the planning process Perry and Lindell 2003.

Earlier research on decision evaluation of strategies in emergency management have primarily been focused on the evaluation of different mitigation strategies, e.g., Tkach and Simonovic 1997; Gupta and Shah 1998; Brouwers et al. 2004. Further, the decision analysis approach toward evaluating response strategies is new as it takes into account the uncertainty with respect to different scenarios as well as refraining from the specification of precise trade-offs between attributes and utility values, cf., e.g., Hämäläinen et al. 2000; Levy et al. 2007.

1.1 Preparedness Plans Components and Activities

In general, a preparedness plan consists of the components or activities listed below, and the plan should specify; what and where an activity will be done, by whom, and who is responsible for delivering the necessary information and resources to carry out the activity in an adequate manner, cf. McLoughlin 1985. In this sense, the plan defines a set of roles which are to be coordinated in the response.

Although the granularity level of plans compared herein is rather low, the method of representation and comparison may be applied on the whole organisational system of sub-parts of it with a higher level of granularity. Thus, the approach to comparing is not restricted to preparedness plans on a high level. Below, the specific roles are derived from the general components of an off-site nuclear preparedness plan on a high level.

DA - Detection and alarm
There is/are some unit(s) responsible for the detection of a possible threat leading to an emergency situation. Detections may come from two distinct types of sources, notifications (DA_n) from outside or from monitoring systems (DA_m). Given that the unit(s) responsible for detecting evaluates the threat to be of sufficient magnitude, an alarm message is sent out to certain destinations.

FC - Forecasting
Given an alarm, there is/are some unit(s) responsible for the forecasting

of the threat's future development. This include both assessing the likely future magnitude (FC_m) of the threat and its spatial distribution over time (FC_s).

CA - Consequence assessment
Given an alarm and forecasts, there is/are some unit(s) responsible for the assessment of consequences of the threat. This include consequences for the general public health (CA_h) and environmental consequences (CA_{en}).

MC - Mobilisation and coordination
Given an alarm, forecasts, and consequence assessments, there is/are some unit(s) responsible for the mobilisation of the ad-hoc emergency organisation operations centre (MC_m),

and some unit responsible for the coordination and maintenance of this centre (MC_c).

WG - Warning

Given a mobilisation, there is/are some unit(s) responsible for the warning the general public by means of various channels. This includes defining the content of the warning (WG_c), releasing the warning to the media (WG_{nm}), and dissemination of the warning and its content to the public (WG_d).

DM - Decision making

Given a mobilisation, there is/are some unit(s) responsible for the decisions of whether or not to initiate various counter-measures based on forecasts and the consequence assessments. The most prominent safety measures under consideration in the case of an off-site emergency are the following:

- Indoor sheltering (DM_s)
- Evacuation (DM_e)
- Control of drinking water (DM_{dw})
- Control of agricultural production (DM_{ap})

PI - Public intervention

Given initiated safety measures, there is/are some unit(s) responsible for the physical interaction with the general public implementing safety measures which calls for direct intervention. This include responsibility for implementing an evacuation (PI_e).

The units and their responsibilities described above are located on different governmental levels, that is *government level*, *federal authority level*, *regional level*, and *local level*. For some of the activities/components it is rather straightforward to assign the various tasks to existing authorities. For example, the role of public interaction (PI_e) in order to complete an evacuation is done by the regional or local police force.

A common way of representing and visualising preparedness plans is by means of flowchart models. A simple flowcharts, as the one shown in Figure 1, consists of agencies (which can be either authorities, regional governments, and municipalities) and two types of directed arcs between. The first arc, depicted as a dotted line, indicates that the plan explicitly states that the predecessor must serve the successor with information necessary for the latter to operate. The second arc, depicted as a filled line, indicates that the predecessor makes decisions, causing an obligation at the successor to implement the decision.

2 Evaluation by Criteria

In this framework, we distinguish between three general categories of criteria which a preparedness plan is evaluated upon: *organisational criteria*, *maturity criteria*, and *effectiveness criteria*. The organisational criteria are derived from findings in social science research on emergency management concerning better-practice properties of the organisational setup for emergency preparedness, with units in several different agencies. The selection of organisational criteria herein is based upon the findings and propositions presented in Quarantelli 1997; Quarantelli 1998; Haque 2000; PERI 2001; Perry and Lindell

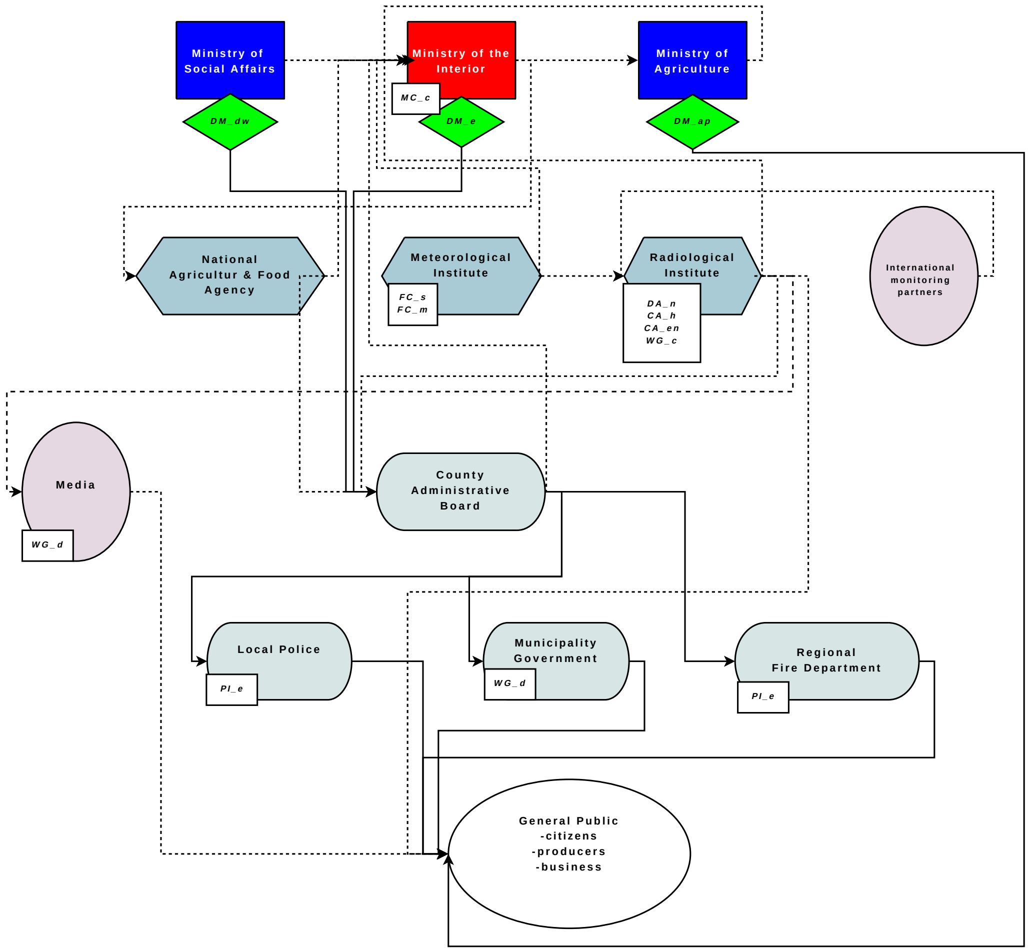

Figure 1: A flowchart model interpretation (including distribution of roles) of a national preparedness plan with respect to an off-site nuclear emergency.

2003. These papers share a common prescriptive objective in that they outline what is of importance for good planning of the emergency preparedness. We do not claim herein that this selection is exhaustive, but it nevertheless serves as a reasonable selection derived from empirical research.

In contrast, maturity criteria are concerned with the, technical and non-technical, activities or solutions planned or implemented and their respective stage of development. Finally, effectiveness criteria are concerned with assessing the anticipated effectiveness of the response with respect to a reasonable scenarios.

Following Parker and Fordham 1996, assessments of the level of fulfillment for each criterion is done upon an *ordinal scale*, ranging from 1 (worst/rudimentary/non-existing) to 5 (best/advanced/coherent/state-of-the-art). Intermediary assessments of 2,3, or 4 can be made in order for more moderate assessments. With respect to the effectiveness criteria, underlying metrics of response effectiveness suggested in Brown and Robinson 2005 are employed, and a table for mapping of these metrics onto the ordinal scale is suggested. It should be noted that due to the use of ordinal scales, it is not meaningful to compute the arithmetic mean or similar kinds of aggregations (such as weighted sums) of a plan assessment and compare these.

2.1 Organisational Criteria

Organisational culture

${}^{O}G_{11}$ - *Resource coordination vs. command & control*

It is a common understanding in emergency management research that the ad-hoc organisation set up between several agencies not should be managed in a military command-and-control fashion. Instead, it is the coordination of resources within autonomous agencies that is important, calling for an overall organisational culture that is open for inter-agency cooperation. This criterion is evaluated upon to what extent the organisational management structure is based on a philosophy of resource coordination rather than command & control.

${}^{O}G_{12}$ - *Inter-agency contracts*

Evaluates to what extent inter-agency cooperation contracts and mutual agreements is set-up in the plan.

Delegations

${}^{O}G_{21}$ - *Decision-making authority*

Due to the inter-agency cooperation and the emergence of new and special tasks that many of the involved agencies need to undertake during and emergency situation, it is important that the planned cooperation between and coordination of involved agencies determines who has the organisational authority for new or anticipated tasks. This criterion is evaluated upon to what extent the decision-making authority for anticipated tasks is addressed in the plan.

${}^{O}G_{22}$ - *Management authority*

Evaluated upon to what extent the management authority for anticipated tasks for anticipated tasks is addressed in the plan.

${}^{O}G_{23}$ - *Delegation of regular tasks*

Motivated in the same way as the former criteria, but concerned with how the emergency preparedness plan clearly delegates responsibility for the anticipated tasks to taken care of by the agencies themselves.

${}^{O}G_{24}$ - *Delegation of non-regular tasks*

Evaluated upon to what extent the delegation of anticipated non-regular tasks, to be taken care of by emergent groups such as volunteers, is addressed in the plan.

Emergency operations centre

${}^{O}G_{31}$ - *Centre set-up*

This criterion is concerned with that the plan explicitly calls for the set-up and maintaining of an emergency operations centre. This criterion is evaluated upon whether or not such a centre is set-up and that a specific authority has the responsibility and preparedness to do so.

${}^{O}G_{32}$ - *Representation in centre*

One important factor is that an EOC member without decision-making power in the member's home authority may in many cases lead to a lower performance of the EOC, see, e.g. Quarantelli 1997. Evaluates to what extent the representation of EOC members are explicitly addressed.

Criterion/ Score	1	2	3	4	5
${}^{O}G_{11}$	Agencies fully trust authorial structure	...	Agencies conduct individual informative procedures	...	Agencies share common view on coordination
${}^{O}G_{12}$	Independent, no agreements	...	Agency liaison	...	Service level agreements set-up
${}^{O}G_{21}$	Scarce knowledge about proper delegation	...	Agency aware about its own authority	...	Fully specified, all agencies fully aware
${}^{O}G_{22}$	Scarce knowledge about proper delegation	... ...	Agency aware about its own authority	... ...	Fully specified mutual agreements
${}^{O}G_{23}$	Scarce knowledge about proper delegation	... ...	Awareness of resources/limitations	... ...	Specified preparations for agencies to expand
${}^{O}G_{24}$	Scarce knowledge about proper delegation	... ...	Awareness of emergent groups tasks	... ...	Specified preparations for emergent groups tasks
${}^{O}G_{31}$	Not addressed	...	Responsible agency informed and prepared	... ...	Fully specified, all agencies fully aware
${}^{O}G_{32}$	Not addressed	... ...	Partial awareness, no designated representation	...	Fully specified, designated representer with authority

Table 1: Organisational criteria assessment table derived from Quarantelli 1998 and Parker and Fordham 1996.

2.2 Maturity Criteria

A similar criteria based approach to evaluating response systems is taken in Parker and Fordham 1996, where a comparison of the development stages of forecasting-, warning-, and response-systems with respect to floods in the European Union is performed. Although other criteria sets could be used, the preparedness and response system for flood emergencies, nuclear emergencies, storm emergencies, tsunamis etc. do not differ as they consist of the same sub-systems, cf., e.g., Parker and Fordham 1996 and Lindell 2000. These are a detection sub-system, a forecasting sub-system, a warning sub-system, and a response sub-system. Due to these general similarities it is suitable to evaluate a general plan with respect to a similar set of maturity criteria as was done for the comparison of flood emergency systems in Europe. See Parker and Fordham 1996 for other rationales for using the criteria set below.

Warning system

${}^{M}G_{11}$ - *Dominance of forecasting vs. warning*

Evaluates the development from a pure forecast dominated planning of the response to an improved and equal balance between forecast and warning response.

${}^{M}G_{12}$ - *Methods of disseminating warnings*

Evaluates the level of development in the methods used for disseminating warnings.

${}^{M}G_{13}$ - *Content of warning messages to public*

Evaluates the level of clarity and information provided in the warning, ranging from a rudimentary content only revealing a general location to a targeted content including location, timing, and severity.

${}^{M}G_{14}$ - *Geographical coverage*

Evaluates the geographical coverage of the warning system indicated as a percentage of total area under consideration.

Criterion/Score	1	2	3	4	5
${}^{M}G_{11}$	Forecast dominant	...	Equal weight	...	Equal and improved
${}^{M}G_{12}$	General broadcast	...	Wardens, agencies, police, fire dept.		Personal, (cell)phone/pager/fax
${}^{M}G_{13}$	Location only	...	Location and timing	...	Location, timing, severity
${}^{M}G_{14}$	$< 10\%$	...	$> 50\%$	...	$> 75\%$
${}^{M}G_{15}$	$< 50\%$	...	$> 75\%$	...	$> 95\%$
${}^{M}G_{21}$	Parochial	...	National with regional variations	...	National and international
${}^{M}G_{22}$	No laws	...	Laws	...	Laws with liability
${}^{M}G_{31}$	Protective, request only	...	Restricted to specific stakeholders	...	Open access
${}^{M}G_{32}$	Minimum, trust in authorities	...	Limited	...	Fully informed, personal preparedness
${}^{M}G_{33}$	Non-existing, media controlled	...	Some media training, guidelines	...	Professional media informers

Table 2: Maturity criteria assessment table conforming to Parker and Fordham 1996.

${}^{M}G_{15}$ - *Demographical coverage*
Evaluates the demographical coverage of the warning system indicated as a percentage of total population under consideration.

Standards and laws
${}^{M}G_{21}$ - *Standards*
Evaluates the existence of national/international standards and the level of coherence with these standards.

${}^{M}G_{22}$ - *Laws relating to EPP*
Evaluates the existence of legal underpinnings regulating the preparations and maintenance of an emergency preparedness plan and response system.

Public relations
${}^{M}G_{31}$ - *Attitudes to freedom of risk/hazard information*
Evaluates the level of public openness with respect to the distribution of information regarding known risks and planned response to the general public.

${}^{M}G_{32}$ - *Public knowledge*
Evaluated upon the degree of public education and knowledge about the warning system and the publics anticipated behaviour in case of a warning.

${}^{M}G_{32}$ - *Reports for the news media*
Evaluated upon to what extent there is a unit responsible for providing the news media with correct facts and information about the situation.

Together the organisational and maturity criteria allow for the identification of where to put efforts toward reaching an inter-agency and integrated emergency preparedness plan with respect to a certain element of threat.

2.2.1 Assessment Example

As an example we present a tentative assessment of organisational and maturity criteria for two Nordic countries' national preparedness plans against an off-site nuclear emergency. We call these two plans N_1 and N_2, where N_1 is illustrated as a flowchart in Figure 1. Assessments in this example are based upon (public) secondary sources in terms of the content in written plans together with summary reports on exercises. These secondary sources are available from web-sites of engaged agencies, such as national rescue services agencies, meteorological agencies, and radiation authorities. However, real assessments of degrees of fulfillment need to be further motivated by primary data such as interviews and reviews.

As the Nordic countries are member states of the International Atomic Energy Agency (IAEA), their respective emergency preparedness planning is heavily influenced by the international standards promoted by the IAEA. However, these standards do not impose a specific way of organising and planning the emergency response, but rather general requirements that should be met of an emergency preparedness plan.

> Jurisdictions of the various orders and levels of government may be laid out in substantially different ways between States. Likewise, the authorities of the various organizations that could be involved in emergency response may be allocated in substantially different ways. IAEA 2002

Furthermore, the standards of the IAEA is not legally binding for member states in cases where the IAEA does not directly assist in the construction of the plan. In fact, in Europe there exists no single structure agreed upon for the emergency preparedness and response organisation Bartzis et al. 2000.

Although the need for emergency preparedness plans in the case of a nuclear emergency has been recognised since the initial constructions of nuclear power plants, the need for inter-agency cooperation on the national and international level was not on the top of the agenda until the Chernobyl disaster in 1986, see, e.g., Barkenbus 1987.

Both N_1 and N_2 emphasise the inappropriateness of managing the response in a strictly hierarchic command & control fashion, as well as the importance of an organisational model facilitating coordination rather than control. Thus, the plans are based on a philosophy of response coordination recognised and agreed upon by involved agencies.

Although the decision making is decentralised to regional authorities, some decisions are restricted to higher level authorities, cf. Figure 1. Thus, the decision making power are specified to the extent of highly anticipated decision problems, and agencies are seemingly aware of the occasional distribution of decision power and autonomy.

There is also a common understanding of the different agencies roles and responsibilities, and each agency is aware of its obligations of delivering information to be used as a basis for decision making. However, what is unclear is the horisontal interaction between agencies, i.e., the interaction between agencies having similar roles but in different regions such as county administrations. This holds for both N_1 and N_2 and with respect to management authority and delegation of tasks. There tends to exist an underlying assumption in the documentation of the preparedness plans that the event is isolated to a single region, leading to a focus on the vertical interaction between local, regional, and national authorities and less on local-local and regional-regional interaction.

Further, the plans strive to design such an organisational model by handing the responsibility for the initial set-up of an operational centre to a designated unit. The set-up of an operational centre is clearly specified for both N_1 and N_2, but only for the latter we have seen a list of high priority participants of the agencies involved but nothing concerning any required authority in the agency they are representing.

An aspect that has been in focus in the development of N_1 and N_2 is monitoring, forecasting systems, and to some extent the warning system. During the latter decade, much work has been devoted toward developing decision support systems with respect to improving both the quality of forecasts and consequence assessments of such forecasts. In the aftermath of the Chernobyl disaster, a number of activities aimed at strengthening the preparedness toward off-site emergencies evolved such as development of decision support systems (e.g., RODOS and ARGOS Bartzis et al. 2000; Hoe et al. 2002) and formulating plans for a well organised emergency response. Warnings are primarily disseminated through eter media as a general broadcast, informing the public about timing, location, and safety measures such as indoor stay.

Overall, N_1 and N_2 are very similar, quite developed and mature according to this assessment example. This could be a result of pressure from the public opinion with respect to nuclear safety following the Chernobyl disaster, resulting in allocation of funds for plan development and maintenance. A summarising conclusion is that both N_1 and N_2 are strong with respect to the inter-agency coordination, but less strong with respect to the communication with the public. Hence, based on this tentative assessment, resources should be allocated for improving the communication between authorities and the public.

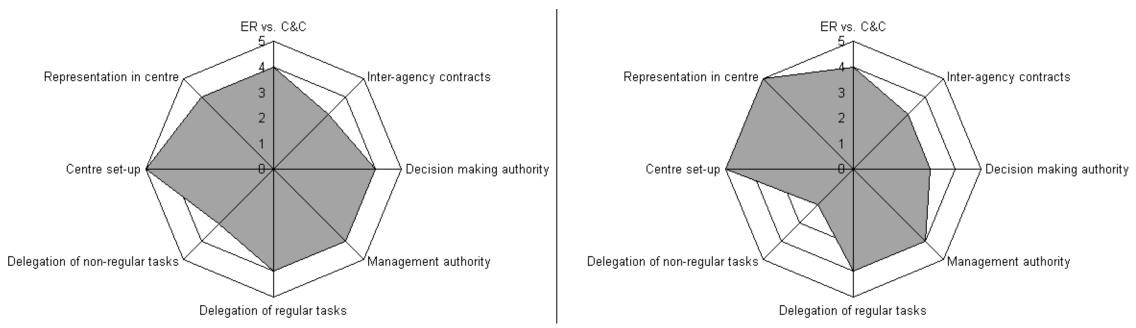

Figure 2: Evaluation of organisational criteria for N_1 and N_2 respectively.

Figure 3: Evaluation of maturity criteria for N_1 and N_2 respectively.

2.3 Effectiveness Criteria

Knowledge of effectiveness involve some method or metrics to measure effectiveness implying that the effectiveness criteria differ from the previously covered criteria in terms of the use of underlying numerical measures. The numerical measures indicate the level of anticipated effectiveness of an executed plan against an undesired but contingent scenario. With respect to planning the procedure of assessing numerical values measuring the anticipated effectiveness of the response is not an easy task, and simulation models may be necessary, see Jain and McLean 2003a; Jain and McLean 2003b for a survey of existing simulation tools for emergency response. Nevertheless, it serves as an important part of preparedness plan evaluation and development, as a particular preparedness plan is to be motivated by means of at least an apprehension of its effectiveness.

Little has been published in the open domain with respect to measuring effectiveness of emergency response. However, a collection of such measures is suggested in Brown and Robinson 2005, adapting a goal attainment approach to effectiveness. The goals in mind for an emergency response are to attain: 1) stabilisation of the scene, 2) preventing further harm on population and property, 3) search and rescue, and 4) safety. Hence, the effectiveness is assessed as to what extent the goals are accomplished, not being concerned with the specific activities undertaken in order to achieve the goals. Further, these effectiveness metrics are scaled with respect to the severity of the scenario.

Some of the effectiveness criteria are evaluated by means of a function $F(t)$ of the time t elapsed from the time t_0 of *execution* of the preparedness plan. Herein, the time of execution of the plan is defined as the *time of the initial warning signal leading to plan execution*. The effectiveness criteria herein thus conform to the suggestions in Brown and Robinson 2005, from which the following set of effectiveness criteria is compiled.

$^{E}G_{11}$ - *Victims found*
A strictly increasing function $F_V(t)$ indicating the percentage of victims found at a time $t \geq t_0$. Level of effectiveness is assessed by means of a given $u_V \in [0,1]$ of interest, such that the lower the value of $F_V^{-1}(u_V)$ the more effective the response.
$^{E}G_{12}$ - *Victims whose condition worsens*
The percentage p_V of all victims whose condition worsen after identification.
$^{E}G_{13}$ - *Property damage identified*
A strictly increasing function $F_D(t)$ indicating the percentage of property damage identified at a given time $t \geq t_0$. Level of effectiveness is assessed by means of a given $u_D \in [0,1]$ of interest, such that the lower the value of $F_D^{-1}(u_D)$ the more effective the response.
$^{E}G_{14}$ - *Property sustained further damage*
The percentage p_D of property that sustains further damage after being identified by responders.
$^{E}G_{15}$ - *Infrastructure functionality*
A strictly increasing function $F_I(t)$ indicating the percentage infrastructure functionality at a time $t \geq t_0$. Level of effectiveness is assessed by means of a given $u_I \in [0,1]$ of interest, such that the lower the value of $F_I^{-1}(u_I)$ the more effective the response.

Thus, an effectiveness assessment can be represented as the quintuple

$$\langle u_V, u_D, u_I, p_V, p_D \rangle \tag{1}$$

Criterion/Score	1	2	3	4	5
${}^{E}G_{11}$	$F_V^{-1}(0.95) > 48\text{h}$	...	$F_V^{-1}(0.95) < 24\text{h}$	...	$F_V^{-1}(0.95) < 6\text{h}$
${}^{E}G_{12}$	$> 50\%$	...	$< 10\%$		$< 1\%$
${}^{E}G_{13}$	$F_P^{-1}(0.95) > 48\text{h}$	...	$F_P^{-1}(0.95) < 24\text{h}$	...	$F_P^{-1}(0.95) < 6\text{h}$
${}^{E}G_{14}$	$> 10\%$	...	$< 10\%$	...	$< 1\%$
${}^{E}G_{15}$	$F_I^{-1}(0.95) > 48\text{h}$	...	$F_I^{-1}(0.95) < 24\text{h}$	...	$F_I^{-1}(0.95) < 12\text{h}$

Table 3: Effectiveness criteria assessment table derived from Brown and Robinson 2005.

consisting of numerical assessments for each effectiveness criterion. Given these measures the table below, mapping the effectiveness measures onto an ordinal scale, *may* be used if the evaluator wish to communicate the assessment results in the same fashion as for the more qualitative criteria presented in previous sections.

2.4 Multiple Scenarios and Robustness

In Godet 2000, a scenario is defined as "a set formed by the description of a future situation and the course of events that enables one to progress from the original situation to the future situation". They can be extreme or moderate both in terms of desirability and likelihood. Exploiting scenario analysis (feared scenarios) with respect to emergency preparedness is not a novel idea. In Bloom and Menefee 1994 the authors distinguish between scenario planning and contingency planning where the latter is defined as planning focused against a "dramatic" event calling for a quick response.

An important part of any planning technique exploiting scenario analysis is the development of scenarios. This is a time consuming and expensive task as construction of a scenario must involve numerous experts. For example, an international exercise of nuclear emergency preparedness takes about two years to prepare, including defining the scenarios OECD 2001. Further, in a construction of a single scenario of radiological emergency developed by the Swedish Emergency Management Agency, SEMA 2005, there were 55 experts from different agencies involved, including, e.g., the customs, the road administration, county administrations, radiological and nuclear institutes, agricultural authorities an so forth. Construction of scenarios and may be aided by techniques developed within the area of soft operations research to handle the numerous expert opinions involved, but often scenarios are constructed in rather unstructured meetings and sessions, see, e.g., Eriksson and Ritchey 2002; Ritchey 2006.

As a preparedness plan is made against a highly undesired scenario, the construction of a preparedness plan by itself is a result of a contingency planning. However, due to the inherent uncertainty of the de facto effects of any catastrophic scenario, of interest for preparedness plan robustness evaluation is to assess the plan against multiple scenarios which may differ from in terms of threat severity, predictability, weather conditions, season of the year etc. Needless to say, any assessment of anticipated effectiveness as described above is dependent on a given degree of severity. The same hold for predictability, as for example, in a potential tsunami emergency the most common warning systems of today cannot predict the amplitude of the wave although the arrival time may be accurately calculated Titov et al. 2005.

So, let $\{\omega_1, \dots, \omega_n\}$ be a set of scenarios, then given a preparedness plan with an associated response strategy, an *effectiveness assessment* with respect to scenario ω_j is the quintuple

$$\mathbf{a}_{\omega_j} = \langle u_V, u_D, u_I, p_V, p_D \rangle_j \tag{2}$$

of assessments for the response effectiveness with respect to ω_i. We may now define response robustness.

Definition 1 *Given a set of scenarios $\Omega = \{\omega_1, \ldots, \omega_n\}$, a set of corresponding effectiveness assessments*

$$\mathbf{a}_\Omega = \{\mathbf{a}_{\omega_1}, \ldots, \mathbf{a}_{\omega_n}\}$$

is robust if there does not exist any $\mathbf{a}_{\omega_j} \in \mathbf{a}_\Omega$, such that for some assessment x_j of $\mathbf{a}_{\omega_j}$ we have $x_k > s_k$, where s_k is a threshold.

of reasonable robustness. *reasonably robust* if it is robust with a relative likelihood greater than r, where r is a relative likelihood threshold.

Deciding upon adequate levels for the robustness thresholds of response effectiveness is an activity to be undertaken by emergency management. The use of thresholds in this manner also provides consistency with the commonly employed ALARP-principle (As Low as Reasonably Practicable) for safety related decision making, as a threshold in the above sense is similar to an ALARP "basic safety limit", i.e., tolerability threshold, see, e.g., French et al. 2005. However, attitudes such as thresholds of this kind can not be expressed independent of consequence assessments given a scenario, anticipated effectiveness of planned response, and costs for effectiveness improval. As there is an important distinction between an effectiveness assessment and a consequence description in that the former is scaled according to the severity of the scenario, whereas the latter is not, assessing consequence descriptions will yield an insight with respect to how high demands we should put on the effectiveness thresholds.

3 Response Strategy Selection Model

A crucial part of any preparedness plan is the associated strategy for the actual response, i.e. the activation of the plan and utilisation of response resources. Needless to say, such response strategies need to be prepared for and thus partly decided upon in advance, leading to decisions regarding techniques employed, location of resources, response capacity, as well as related investment and maintenance costs. The choice of a particular response strategy should be based upon a knowledge of its anticipated effectiveness with respect to a certain element of threat and the threat's potential impact in terms of reasonable consequences, weighted against anticipated costs. In order to do this in an analytical fashion, formal descriptions of these elements need to be defined.

3.1 Catastrophe Description

In Brown and Robinson 2005 there is a promising but less formal discussion on metrics describing a generalised consequence of a disastrous or catastrophic scenario. Therein, they delimit the measurement to an affected geographical area, and suggest measuring a scenario through its effects on the lives of the affected population and property in this area.

In the following, we will denote a particular consequence of a contingent scenario ω_j with c_j, and will let A be the area under consideration. For the effects on human lives, let A_{Pop} be a number representing the human population in A, and let ${}^{I}A_{Pop}$ be the percentage of A_{Pop} that sustains injury.

The same reasoning applies for property damage. Let A_{Pty} be a number representing the potential property in A and let ${}^{D}A_{Pty}$ be the percentage of A_{Pty} that sustains further damage. Here, A_{Pty} may be given in monetary terms.

The injuries are further categorised into a type and a level of severity. Let T_I be a set of injury types and S_I be a set of severity levels. For example, injury types in T_I include, e.g., cardiac injuries, crushing injuries, and respiratory injuries. The levels of severity in S_I is naturally ordered and may, e.g., range from mild to deadly. Hence, a particular injury is specified from an element in $T_I \times S_I$, and for a catastrophe description, we let f_I be a discrete distribution over the finite set $T_I \times S_I$.

Analogous for property damage, a particular damage is specified as an element in $T_D \times S_D$ where T_D is a set of property types and S_D is an ordered set of damage severity. Property must not be delimited to constructions, but also include, e.g., farming areas and forests. Again for the description, we let f_D be a discrete distribution over finite set $T_D \times S_D$. See Figures 4 and 5 for examples.

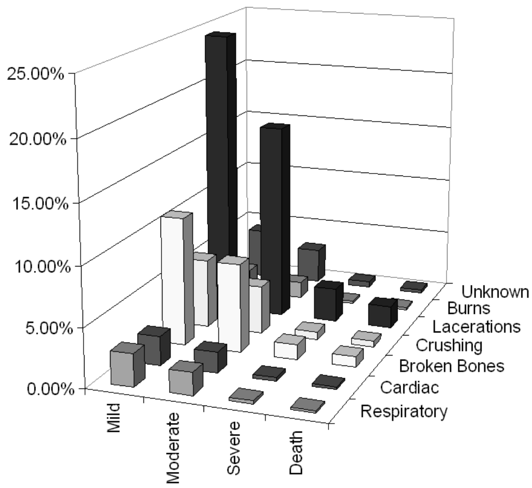

Figure 4: f_I visualised as a histogram with respect to injuries. Adopted from Brown and Robinson 2005.

The straightforward interpretation of the above reasoning is to formally represent a particular consequence c_j of a catastrophic event by means of the different tuples. The health aspects of a consequence is represented by means of the triplet $\langle A_{Pop}, {}^{I}A_{Pop}, f_I \rangle$. Similarly, the property damage aspects of a consequence is represented by the triplet $\langle A_{Pty}, {}^{D}A_{Pty}, f_D \rangle$. We can now define a catastrophe description.

Definition 2 *Let c_j be a consequence, then the pair*

$$\Big(\langle A_{Pop}, {}^{I}A_{Pop}, f_I \rangle, \langle A_{Pty}, {}^{D}A_{Pty}, f_D \rangle \Big)_j$$

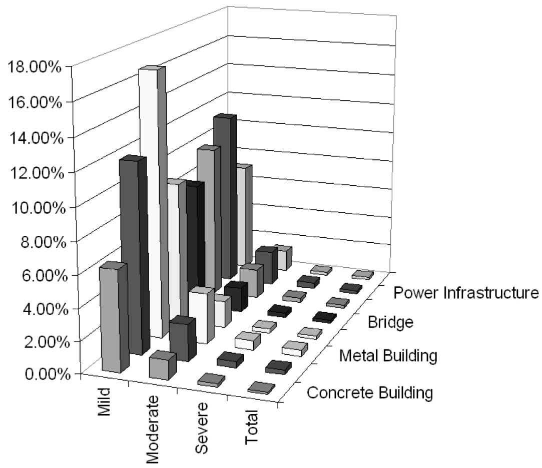

Figure 5: f_D visualised as a histogram with respect to property damage. Adopted from Brown and Robinson 2005.

is a catastrophe description for c_j.

3.2 Support for Strategy Evaluation and Choice

The choice of a particular response strategy from a set of alternative strategies $\{R_1, \ldots, R_m\}$ may be seen upon as a decision under risk where the conducted consequence assessments, yielding catastrophe descriptions, acts as a basis for the decision as assessing catastrophe descriptions is a kind of risk analysis. Then a consequence c_{ij} is the result of a pair (R_i, ω_j) of a particular strategy and scenario, i.e. a consequence is given by the mapping

$$(R_i, \omega_j) \mapsto c_{ij}$$

where each c_{ij} is (partly) assessed by means of a catastrophe description. One way of obtaining catastrophe descriptions for each c_{ij} in a reasonable way would be to let R_0 be the null strategy (a response strategy is absent), then first assess each $c_{0j}, 1 \leq j \leq n$, later assessing each c_{ij} from having the associated effectiveness of each R_i operate on each c_{0j}.

As the cost for each R_i should be taken into account in the decision evaluation, each c_{ij} should be evaluated upon by basis of a catastrophe description and the cost of R_i. We will not be concerned with methods for arriving at adequate cost levels for preparedness herein, but rather assume that assessments of the cost x_i for preparedness R_i may be done, although it may be subject to uncertainty. Having a decision theoretical representation such as the one outlined above, we can allow for an analyst to evaluate related costs of different response strategies against their anticipated performance with respect to different scenarios.

3.2.1 Decision Support Methodologies

At present, there are essentially two approaches toward supporting such decisions in an analytical fashion; cost/benefit analysis (CBA) and decision analysis (DA). The underlying idea of CBA is to assign monetary values to both expected costs and benefits associated with each decision alternative and simply rank the alternatives according to the expected monetary values, i.e. the difference between monetary benefits and costs. In this case, as for many other, this inevitably leads to difficult assessments of the value of a "statistical life" and of different types of "statistical injuries" for which there are no market prices considered to be objective. In such cases, prices are commonly obtained from various choice experiments such as asking the general public for its willingness to pay for safety French et al. 2005.

A further issue with using CBA in this setting is the treatment of uncertainty. For a CBA approach, we would obtain expected costs for the development and maintenance of a certain response capacity. We would also need an assessment of expected benefits, measured as a monetary value. Now due to the high uncertainty regarding the probability of a catastrophic event occurring during a time period of, say the coming 5 years, it is hard to obtain expected benefits due to insufficient statistical data.

Decision analysis approach is generally considered as the application of theories of rational choice on real world decision problems, see, e.g., Keeney and Raiffa 1976; French 1986. When using the decision analysis approach, the analyst is to represent the desirability of each c_{ij} by means of a real-valued utility function u defined on the set of all c_{ij}. In this setting, c_{ij} is not preferred to c_{kl} if and only if $u(c_{ij}) \leq u(c_{kl})$.

Multi-attribute utility theory (MAUT) admits for a decomposed utility function in terms of several "attribute specific" utility functions being aggregated into a single one. Hence, each consequence c_{ij} is evaluated upon a set $\mathbf{G}$ of pre-defined attributes, preferably chosen in a manner facilitating the elicitation of preferential statements. For example in the setting treated herein, one reasonable such attribute is the cost, such that its utility function maps a lower cost to a higher utility value.

If uncertainty with respect to future outcomes is present, this is treated by means of probability distributions over the set of possible outcomes, and the decision maker's attitude toward risk derived from such uncertainty is, ultimately, incorporated in the utility functions. The aggregation of several utilities is done relative to attribute weights (or scaling constants), reflecting each attribute's importance in relation to the other attributes. The aggregation will impose a number of independence conditions on the attributes (which sometimes may be hard to justify). The decision alternatives are finally ranked according to their expected (aggregated) utility, this is commonly referred to as the utility principle.

In Aven and Krte 2003; French et al. 2005 there are investigations on the appropriateness of these two approaches to decision support in similar domains, both in terms of their practical usefulness and their philosophical foundations. The essence of the more critical conclusions of these investigations can be briefly summarised into:

- CBA cannot find objective prices in practice, and it treats uncertainties in an ad-hoc manner.
- DA is difficult to carry out in practice due to the elicitation of utility values and trade-offs, and results are hard to communicate. It treats the decision-maker as a single entity.

We will not add further to this debate, but argue that way to improve the pragmatic properties of DA approaches in the current domain is to relax the requirements on the input statements though allowing for imprecise statements.

3.2.2 Supporting Imprecision

There are essentially two reasons for relaxing the requirement for precise numerical utility-estimates on consequences. First, the quality of the assessments necessary for obtaining catastrophe descriptions may be deemed to be poor, i.e. sufficient data may not be available leading to incomplete catastrophe descriptions Ekenberg et al. 2001. Second, the elicitation of risk attitudes from decision-makers is error prone, the resulting utilities seem to be highly dependent on the method and format used in the elicitation Riabacke et al. 2006. Furthermore, dealing with catastrophic consequences as is the case here seems to significantly increase the problematic issues of obtaining equitable utilities in the elicitation process Mason et al. 2005.

A promising direction for a practical decision analysis of the decision problem herein is therefore to employ the decision analytical framework suggested in Danielson and Ekenberg 1998; Danielson 2005; Larsson et al. 2005; Danielson and Ekenberg 2007, also implemented in a software tool Danielson et al. 2003; Danielson et al. 2007. In brief, that framework is based upon classic decision analysis, but allows for interval-valued utility statements, interval weights, interval probabilities, as well as comparative statements between variables such as "c_{ij} is better than c_{kl}", "the scenario ω_i is more probable than the scenario ω_j" and "A_{Pop} is more important than A_{Pty}". Thus, the method can be seen upon as the employment of a frugal multiattribute model decreasing the efforts needed in elicitation of input statements, cf. Katsikopoulos and Fasolo 2006. This allows us to be less concerned with the absolute probability of a catastrophic event actually occurring, as the lack of statistical data with respect to such events lead to that such uncertainties can be seen upon as immeasurable, cf. Ekenberg et al. 2001; Johansson and Malmns 2004. Instead, we put emphasis on expressing relative likelihoods of different scenarios, given the occurrence of a catastrophic event.

3.2.3 Strategy Evaluation

Relaxing the requirement for precise estimates of utility, weight, and likelihood statements will lead to that it is not clear how to infer an unambiguous ranking of the strategies, as is the for the classical utility principle. The outlined approach to decision evaluation is therefore based on a three step process. The initial two steps discarding strategies deemed as simply unacceptable or inferior according to reasonable discrimination rules. If more than one strategy remain after these steps, the final step takes advantage of decision evaluation methods supporting imprecise input statements. In the following, we will let $\mathbf{G}$ be the set of attributes by which a consequence c_{ij} is evaluated upon, i.e. the evaluation attributes.

Step 1 – Discard strategies violating stipulated thresholds

The initial evaluation step calls for that the decision maker should explicitly state performance thresholds, expressing minimum requirements that a response strategy should fulfill in order to be acceptable. These thresholds are assigned relative to a chosen sub-set of the attributes in $\mathbf{G}$. For example, let ${}^{R}G_i \in \mathbf{G}$ where ${}^{R}G_i$ is an attribute measured by means of ${}^{I}A_{Pop}$, then a threshold with respect to this attribute can be stipulated as a condition ${}^{I}A_{Pop} \leq 10\%$. This condition should be fulfilled for all consequences c_{ij} of a particular strategy R_i in order for R_i to be deemed an acceptable strategy, i.e. not violating the threshold. With respect to decision theory, such thresholds are analogous to stipulating risk constraints as a complementary way of modelling risk aversion, see Ekenberg et al. 2001 for a comprehensive treatment.

Definition 3 (Acceptability) *Let* $\mathbf{G} = \{^R G_1, \ldots, ^R G_k\}$ *be the set of evaluation attributes, and let* $\mathbf{T} = \{T_{s_t}\}, s_t \in \{1, \ldots, k\}$*, be a set of performance thresholds such that* T_{s_t} *is a performance threshold for* $^R G_{s_t}$*. Then* R_i *is an acceptable response strategy if there does not exist any* c_{ij} *such that the performance of* R_i *with respect to* $^R G_{s_t}$ *violates* T_{s_t} *for all* s_t*.*

If the set of acceptable strategies is empty after this step, then either the decision maker has to accept lesser demanding performance thresholds, or search for new strategies.

Step 2 – Discard dominated strategies
Dominance is a straightforward concept. It is included here as a fundamental condition for rationality.

Definition 4 (Basic dominance) *Let* $\mathbf{G}$ *be the set of evaluation attributes.* R_s *is dominated by* R_t *if (and only if) for each scenario* ω_j*,* c_{sj} *is not preferred to* c_{tj} *with respect to all evaluation attributes, and at least one* c_{tj} *is preferred to* c_{sj} *for some evaluation attribute.*

As dominance is a too strong requirement for many situations, i.e. the set of non-dominated strategies will consist of more than one strategy in most complicated selection problems. This calls for the need to employ other decision evaluation techniques in order to support the selection of a strategy. This is the matter for Step 3.

Step 3 – Evaluate acceptable and non-dominated strategies
In the body of computational methods for decision analysis purposes presented in Danielson 2005; Larsson et al. 2005; Danielson and Ekenberg 2007, sometimes referred to as the DELTA framework, imprecise input is provided by means of sets of linear constraints. For instance, the utility of c_{ij} with respect to attribute $^R G_k$ being between the numbers a and b is expressed as $^k u_{ij} \in [a, b]$. The approach also includes comparative relations – a measure (or function) of c_{ij} is greater than a measure (or function) of c_{kl} is expressed as $^k u_{ij} \geq^k u_{kl}$. Similar statements are allowed also with respect to attribute weights as well as probabilities on scenarios. Hence, each statement (probability, utility, weight) is represented by one or more constraints. On top of this, it is possible (but not necessary) to assign a most-likely-point for each variable.

The set of evaluation attributes $\mathbf{G}$ may here be re-defined in order to facilitate the incorporation of available information in the preferential statements between consequences. For example, although a statement such as "$A_{Pop_{ij}}$ is preferred to $A_{Pop_{kl}}$" is meaningful, a statement such as "$\langle A_{Pop}, ^I A_{Pop}, f_I\rangle_{ij}$ is preferred to $\langle A_{Pop}, ^I A_{Pop}, f_I\rangle_{kl}$" takes a wider spectrum of information into account, given that this information is available.

The techniques employed for evaluation will indicate a reasonable preference order of the response strategies, with embedded sensitivity analyses. See the example below for a brief presentation, and Danielson 2005; Boeva et al. 2005; Idefeldt et al. 2006 for more comprehensive treatments of these evaluation techniques.

3.2.4 Modelling and Evaluation Example

Consider a case with three acceptable and non-dominated response strategies under consideration, label this R_1, R_2, R_3. The strategies is are part of a planned preparedness with respect to a particular element of threat, whose impact on the affected area and population differs between four developed scenarios $\omega_1, \omega_2, \omega_3, \omega_4$. Each response strategy R_i is associated with an cost estimate x_i for the development and maintenance of the preparedness during a given time-period, for example the period until a new plan revision. Each x_i is assessed as an interval together with an estimation of a most likely cost. In this example, a consequence c_{ij} is evaluated upon three attributes, two sub-sets of the components of a catastrophe description and strategy cost. Thus, the evaluation attributes in $\mathbf{G}$ are:

${}^{R}G_1$ Maintenance cost attribute, assessed by means of the cost x_i

${}^{R}G_2$ Population attribute, assessed by means of $\langle A_{Pop},^{I} A_{Pop}, f_I\rangle_{ij}$

${}^{R}G_3$ Property damage attribute, assessed by means of $\langle A_{Pty},^{D} A_{Pty}, f_D\rangle_{ij}$

A simple attribute tree with the attributes under consideration is shown in Figure 6[1].

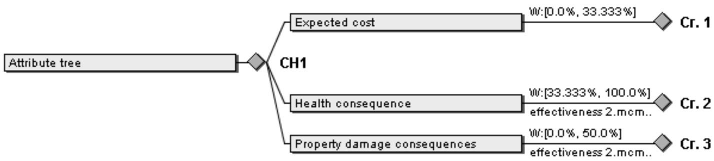

Figure 6: Attribute tree.

As the prepared response strategies (modelled as decision alternatives) score different against different scenarios, a simple decision tree such as the one seen in Figure 7 is associated to the lower two attributes of the attribute tree shown in Figure 6.

For example, given the distribution components shown in Figure 8 together with $A_{Pop_{11}} = A_{Pop_{21}}$, ${}^{i}A_{Pop_{11}} = 1.6\%$, ${}^{i}A_{Pop_{21}} = 2.1\%$, a decision maker may state that, with respect to the health attribute, c_{11} is not preferred to c_{21} due to the higher number of deaths and severe injuries.

A DELTA evaluation is shown in Figure 9, as a pairwise comparison of R_1 and R_2. With the exception of the cost attribute, only comparative relations as input statements with respect to weights, relative likelihoods of scenarios, and utilities of consequences have been made. The evaluation on the left hand side, where cost is the least important attribute, strongly supports the statement that Strategy R_2 (Alt. 2) is preferred to Strategy R_1 (Alt. 1). This can be understood from the gray area's significant presence below the horizontal axis. The evaluation on the right hand side where cost is considered to be the most important attribute, show little support for preference in any direction.

The level of intersection shown in the evaluations, ranging between 0% 100%, and can be seen upon as a stability measure of the proposed preference order given the provided input Idefeldt et al. 2006. The higher the intersection level, the less stable the suggested

[1]Screenshots of tree models and evaluations come from the decision software presented in Danielson et al. 2003

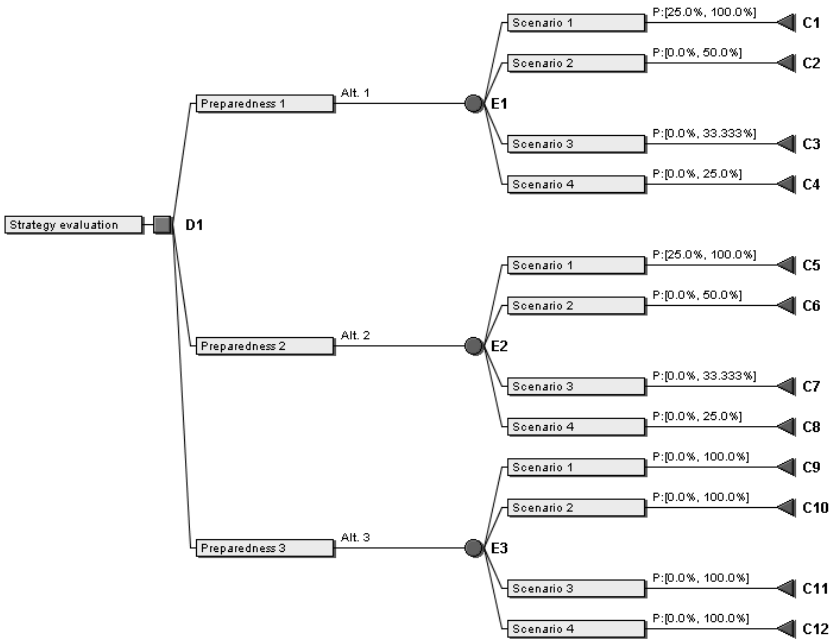

Figure 7: Attribute specific decision tree. In this three c_{11} is represented by C1, c_{21} is represented by C5 etc.

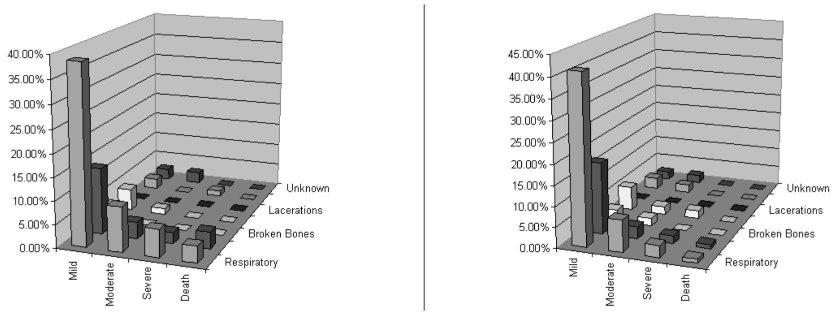

Figure 8: Visualisation of the f_I component of two consequences c_{11} and c_{21}.

preference order. In order to obtain a higher degree of stability, the input need to be revised with a lower degree of imprecision. For this purpose, methods incorporated in the decision framework supporting the identification of variables contributing the most to ranking instability may be employed, such as tornado diagrams Idefeldt and Danielson 2007.

4 Concluding Remarks and Further Work

The criterion based approach toward evaluating an emergency preparedness plan is suitable for both self-assessments as well as second party done by monitoring agencies. Evaluations can be done across different regions, different elements of threat, and time. The approach facilitates the evaluation and comparisons or larger sets of plans which is necessary in order to obtain an overview of general preparedness.

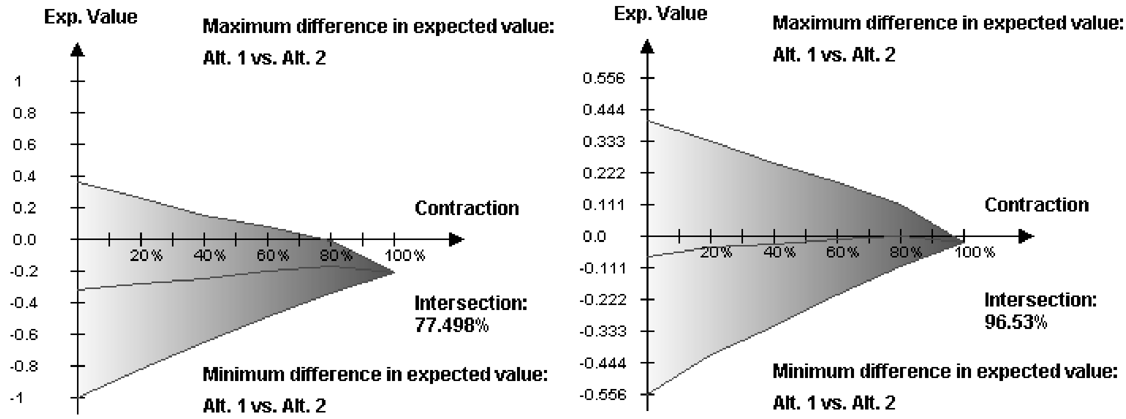

Figure 9: Comparison of two strategies R_1 and R_2.

Further, a new decision analysis approach for the selection of response strategies is presented, refraining from the use of precise utility values and specifications of trade-offs. The decision analysis method can be used as a complement to cost-benefit analyses in the evaluation and selection of cost effective and reasonable response strategies. This could add valuable information to an emergency management review when there exists several different response strategies under consideration.

As an important requirement for both the effectiveness assessment and the decision analysis component is the construction of scenarios and assessing the effectiveness of different response strategies yielding a final consequence. This is not a trivial task, and leave room for further research issues including finding suitable methods facilitating development of equitable scenarios and simulation models with respect to different catastrophic events.

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