Robust emergency management strategies: Supporting interdependent decisions

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Abstract

Due to the complexity of emergencies, interdependencies between decisions are often neglected despite their importance. This paper aims at supporting decision makers in considering the interdependencies and addresses the problem of time: decisions depend on the time and information available, and the timing of decisions can influence on their consequences. To account for the requirements in different phases of an emergency, two approaches are presented.

If the information is highly uncertain and time is critical, it can be advantageous to choose an easily adaptable option. To make the trade-off between choosing a seemingly optimal rigid solution and a flexible option transparent, an approach that is based on the value of flexibility is introduced. If better information and more time are available, a scenario-based approach to sequential decision making is proposed, which supports decision makers in choosing robust alternatives while taking into account the goals of several organisations.

1. Introduction

Every decision is related to time: it takes time to make a decision, time passes until the consequences occur, and in many cases decisions need to be revised during their execution [1]. These temporal aspects of are particularly relevant in emergencies: there is limited time to process large amounts of information, and the situation evolves dynamically [2, 3]. With the rise of ICT systems, the integration of knowledge and information from geographically dispersed experts across organisations has become increasingly important [4, 6]. A major challenge is the gathering of information from various sources and its processing into meaningful assessments [3]. Hence, the need for (computational) support to organise, evaluate, share and represent information grows [3, 5, 6, 7].

Often the assumption is made that decisions are taken at a single point in time and that the events that affect their results can be modelled exhaustively [5, 8]. In practice, however, each choice affects the alternatives feasible in future and the consequences of these alternatives [6]. Hence, decisions should be described as a nested series of interdependent decisions [6], making the importance of aligning decisions in terms of measures and timing should transparent. As strategic decisions are far-reaching in terms of consequences and affect all future operations [7, 8], this paper focuses on strategic decisions.

To support decision makers in aligning their strategies, this paper presents two approaches, which are tailored for different phases of an emergency. The first approach assesses the flexibility of alternatives. It focuses on the early phases when information is highly uncertain. This approach is complemented by scenario-based approach that evaluates consequences of interdependent decisions over time. This approach is designed for the later phases, when more information is available and time is less critical.

The next section provides information about the most common techniques for sequential decision making and outlines an approach for distributed scenario construction that provides the basis for the flexibility analysis and scenario-based decision support described in the subsequent sections. All theoretical considerations are illustrated by an emergency management example.

2. Background

This section discusses the most common techniques for sequential decision making and presents an approach for distributed scenario construction. The scenarios are the basis for the evaluation of alternatives, which will be illustrated by the example.

2.1. Sequential decision making

According to the rational decision making paradigm, decision makers should choose the sequence of decisions that maximises the expected utility [9, 10]. This approach requires full knowledge of the prefer-
quences and utility functions [9]. Furthermore, it assumes implicitly that the problem is well-defined, i.e., all relevant future states, events, actions and results are known or can be characterised by probability distributions [11]. In this (probabilistic) context, Sequential Decision Making (SDM) provides a framework for modelling series of decisions. The most prominent SDM methods are influence diagrams and decision trees [12, 13]. Both methods are usually applied for mono-criterion problems [14], as with each criterion the complexity increases (exponentially for decision trees, linearly for Influence diagrams). In some cases, super value vertices are used to evaluate the options under multiple objectives. These approaches are mostly founded on Multi-Attribute Utility Theory [13, 15].

Another problem of SDM is related to timing issues: usually, it is not known a priori how many decisions will be made and when each piece of information will be available, so additional assumptions increasing the complexity need to be made [1].

Additionally, there are doubts concerning the application of probabilistic techniques for emergency management. In strategic decisions, there is usually no self-contained model covering the necessary domain knowledge for all eventualities [18], and the available data is heterogeneous [4]. Interdependencies make it difficult to attribute consequences clearly a decisions. Additionally, the elicitation of probabilities can be prone to cognitive biases [20].

For these reasons, this paper proposes two approaches that integrate interdependencies and the temporal context of decisions targeted at different phases of the emergency (Sections 3 and 4). Prior to that, Section 2.2 outlines a scenario construction method that is the basis for both approaches.

2.2. Distributed robust decision support

To use of scenarios for strategic decisions in time-bound situations that require the integration of information from various sources this paper uses a distributed approach, which is briefly outlined here; more detailed information can be found in [3, 22, 23].

2.2.1. Scenario construction and evaluation.
To elicit the decision makers’ perspectives on the decision and their information needs, the problem is structured by an attribute tree [6]. An attribute tree provides a structured breakdown of an abstract overall objective onto attributes that enable (quantitatively) measuring in how far each goal is achieved. As the attributes are a means to operationalize the consequences of a decision, they are considered as focus variables that steer the scenario construction: the process is designed such that for each alternative $a_i$ at least one consistent set of values for all focus variables is determined.

Per focus variable, experts (humans or automated systems) are identified that can provide information relevant to assess its possible values [21, 22]. These experts may themselves require further information. The decision support system successively identifies further experts, who registered beforehand in a “yellow pages system” and stated that they are able to provide the required information. The experts are linked in workflows that structure the way the information is shared and processed. These workflows can be represented as directed acyclic graphs (DAGs) [3], which enable distributed scenario construction in a bottom up manner: the experts are provided the input information they require and are asked for their assessments of possible values. If they are uncertain about the value a variable may have, they are asked to provide multiple values that explore the scope of possible developments [3]. The individual assessments are combined to meaningful scenarios: each scenario is one plausible, internally consistent description of the situation and its potential consequences. By using the attribute tree and techniques from Multi-Attribute Decision Making (MADM), the scenarios are evaluated and a ranking of alternatives is derived. In this manner, a robust alternative that performs sufficiently well for all considered scenarios [25] can be identified and chosen.

This approach to scenario-based decision support configures workflows for each specific problem. In this manner, it includes the key drivers of the situation, the best available expertise, specific evaluation criteria, alternatives, and preferences. In contrast to monolithic models, this approach can be adapted flexibly to the actual situation. This is particularly important when the situation is unforeseen and evolves dynamically. This approach does, however, assume that capable experts are available and collaborate via ICT systems, e.g. in a professional social network [24, 28].

2.2.2 Example application. Throughout the paper the example described in the following is illustrates the theoretical considerations. It has been developed with experts from European emergency management authorities and combines results from two research projects.

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An earthquake caused, amongst others, a leak in a gas pipeline, and there is the danger of an explosion. The reparation of the pipeline is a risky task, and the number of people in the vicinity of the leak should be kept low. A gas power plant in the area depends on the pipeline: if the leak is not repaired on due time, there is the risk of large scale power blackouts with important consequences on critical infrastructures such as health or transportation. To solve the problem, two strategic decisions need to be made.

dec 1 How to protect the population in the surrounding areas (evacuation, sheltering ...)?

dec 2 How much resources should be dedicated to the leak reparation?

As per problem different organisations and are involved, the decisions may be made in an isolated manner, although they are interdependent. Additionally, the dynamics of the situation plays an important role, e.g., the number of people in the areas potentially affected by the explosion, the time until leak is repaired (increasing risk of power blackouts), and the duration of these blackouts (consequences increase exponentially with the duration).

Figure 1 shows the DAGs for scenario construction if both problems are represented in an isolated manner. It shows how information from various local experts is combined to assess the focus variables and reveals interdependencies. First, both problems use a common pool of resources. Second, the possibility to influence on the explosion chance variable for dec. 1 and population presence for dec 2 are not exploited. The following sections describe two methods that enable integrating the interdependency of decisions and the role of time.

3. Flexible decisions

Choices are frequently made between alternatives that imply different degrees of future commitment. A strategy whose initial decisions limit the future options as little as possible can have advantages when uncertainties are important [24]. When comparing strategies that imply different time horizons (e.g., a short term alternative that leaves the future largely open vs. one with a longer term impact that forecloses further options), their performance is often measured by probability distributions of their respective payoffs over time [27, 28]. This is, however, difficult in emergencies when probabilities are hard to assess (cf. Section 2.1).

Therefore, this paper focuses on the flexibility of alternatives. Intuitively, a flexible strategy should be preferred over a rigid one, for it offers the possibility to adapt the plan upon receiving new information. In this sense, flexibility limits the risks of an early commitment [2]. This is of major importance in emergency management. Particularly in the early phases, little is known about the incident and its future development. As the often uncontrollable and sometimes unforeseen events unfold, more information becomes available about the situation, its possible developments, and the preferences of the actors. Along with the updated information, possible future developments that are approved by the decision makers and therefore aspired can be identified, and alternatives that facilitate achieving these states can be determined. In the light of the new or updated information, it can be appropriate or even necessary to reconsider, re-evaluate and modify the as yet unimplemented stages of the emergency management strategy. If the possibility of adapting and revising the strategy has not played a role in its specification, however, desired outcomes may not be achievable.

3.1. Analysing the flexibility of an alternative

After these general considerations, flexibility is defined more precisely in this section. Flexibility can be defined as the property of a decision for an alternative $a_i$ that characterises the future scope of possible action given that $a_i$ is implemented at time $t_j$ [2]. Discretising $[t_0, t_f] = \{t_0, t_1, ..., t_T\}$ ($t_f$ denotes the time when the emergency is considered as resolved), the flexibility of $a_i$ at any time step $t_j$ can be characterised by investigating the set of feasible alternatives $\mathcal{F}(\cdot | J)$ that can be implemented at $t_j > t_i$, if $a_i$ was imple-
mented at \( t_i \). Assuming that \( FA^{ij} \) can be determined for all \( j (i<j \leq T) \), the flexibility of \( a_i \), denoted \( \phi(a_i) \), is

\[
\phi(a_i) = \frac{1}{T - i} \sum_{j=i+1}^{T} \left( \frac{|FA^{ij}| - \min_{a_m} |FA^{mj}|}{\max_{a_m} |FA^{mj}| - \min_{a_m} |FA^{mj}|} \right)
\]

The normalisation with respect to the number of feasible options for any other alternative \( a_m \) ensures that the \( \phi(a) \) is a mapping to \([0, 1]\).

The feasibility of the alternatives \( a_i \) at time \( t_i \) may depend not only on \( a_i \), but also on events beyond the control of the decision makers, e.g., meteorological conditions, or on further decisions made in \([t_i, t_j]\) (e.g., at another hierarchical level or in another organisation). If the relations between these interdependent decisions are made transparent, the decision makers or higher level authorities can align the decisions. When several organisations that may pursue different goals are involved, making dependencies explicit and assessing the consequences of a decision across organisations (in terms of flexibility or in terms of a detailed evaluation, cf. Section 4) can facilitate cooperation and collaboration [11, 4].

To assess the flexibility of alternatives, values of all relevant variables must be determined, their interdependencies and possible developments must be characterised. To this end, the distributed scenario construction method presented in Section 2.2 is used. The focus of the scenario construction for the flexibility assessment is finding answers to the questions:

- Which are the prerequisites that are required for the implementation of an alternative?
- Under which circumstances are these prerequisites not fulfilled?

Here, the scenario construction investigates the feasibility of further options (and not a detailed evaluation of alternatives as in Section 2.2). As this assessment requires less and less detailed information and as it is not necessary to elicit focus variables from the decision makers, it is possible to build the DAG (capturing the scenario structure in terms of information flows) before the emergency actually occurs (e.g., by referring to guidelines, handbooks), so that the scenarios construction can be accelerated.

The scenario construction results in a set of scenarios \( SS \), which enables determining the flexibility of each alternative. To control the potential combinatorial explosion and to derive significant results, it is assumed that none of the further alternatives \( a_i \) in the set of alternatives \( A \) whose flexibility is assessed is implemented (i.e., if \( a_i \) is assumed to be implemented in \( S_k \), no further \( a_i \) is allowed to be part of \( S_k \)). The scenario construction finishes, when for each alternative and each scenario the number of feasible alternatives at each time step \( t_j \) is determined. For each scenario \( S_k \), the flexibility of \( a_i (i<T) \) given the occurrence of events described in \( S_k \) is:

\[
\phi(a_i, S_k) = \frac{1}{T - i} \sum_{j=i+1}^{T} \left( \frac{|FA^{ij,k}| - \min_{a_m} |FA^{mj,k}|}{\max_{a_m} |FA^{mj,k}| - \min_{a_m} |FA^{mj,k}|} \right),
\]

where \( |FA^{ij,k}| \) denotes the number of feasible alternatives at time \( t_j \) given that \( a_i \) is implemented at \( t_i \), and that the variables at time \( t_j \) have the values as in \( S_k (t_j) \); \( S_k \) is any scenario in \( SS \) and used for normalisation purposes.

### 3.2. Analysing the value of flexibility

To come to an overall rating of flexibility, all scenarios need to be considered. Analogous to scenario-based approaches for evaluating alternatives, the flexibility of \( a_i \) can be characterised by

\[
\phi(a_i) = \sum_{S_k \in SS} \omega_{ki} \phi(a_i, S_k),
\]

where \( \omega_{ki} (0 \geq 0) \) denotes the relative importance of scenario \( S_k \) assuming that \( a_i \) is implemented. Given the multitude of scenarios, these weights cannot be elicited directly, and this paper suggests using the value of flexibility in each scenario to determine \( \omega_{ki} \).

To assess the value of flexibility it is helpful to determine first the value of control (VoC). Originally, the VoC has been designed to answer the question how much a rational decision maker should be willing to invest to control the behaviour of one uncertain random variable, for which a probability distribution is known [10, 26]. Adapting this concept for the scenario framework, here, the VoC of \( a_i \) at \( t_j \) should be interpreted as an analysis of how much (rational) decision makers would be willing to invest (in terms of effort, resources or cost) to replace the values of all uncertain variables in \( S_k \) at \( t_j \) to their best possible value (with respect to the overall objective) under the assumption that \( a_i \) was implemented at \( t_i \).

The VoC can be modelled and elicited from the decision makers on the basis of two components: the consequences and the likelihood of a variable \( x_k \) having a specific value \( v(x_k) \). Emergencies are typically complex and highly uncertain, which implies that the impact of a variable’s value is hard to assess and that it is difficult to derive probabilities for \( v(x_k) \). Therefore, the (direct) elicitation of the VoC as a willingness to invest is prone to the use of heuristics and biases, and approaches that adapt the basic concepts and facilitate the assessment of consequences and likelihood need to be developed.

### 3.2.1. Consequences

A measure to determine what decision makers would be willing to commit to switch from an alternative \( a_i \) to another alternative \( a_j \),
is the regret [27]. In the scenario-based approach to robust decision making (cf. Section 2.2), the impact of sets of uncertain variables is operationalised in terms of the evaluation of the potential consequences \( p(a_i, S_k) \) for an alternative \( a_i \) and a scenario \( S_k \). This evaluation takes into account the preferences and enables the regret \( \rho(a_i, S_k) = \max_{a_j \in A} \left( p(a_j, S_k) - p(a_i, S_k) \right) \) to be determined.

As the scenarios are designed to assess the feasibility of alternatives, they do not necessarily contain the complete DAGs for the evaluation. In these situations, indicators can be used as proxy variables for assessing the impact of a change in a variable’s value on the ranking of alternatives [22]. In this manner, indicator-based performance assessments \( \bar{p}(a_i, S_k) \) can be derived. As the performances \( \bar{p} \) and \( p \) are normalised, \( p(a_i, S_k) \in [0, 1] \).

The regret can be interpreted as a measure of potential gap in impact of a strategy starting with \( a_i \) compared to the best possible other. As only the impact of the decision on \( a_i \) is investigated here, no further options are assumed to be implemented.

If the regret is large, it is important to implement further measures that address and balance the weaknesses of \( a_i \) hence \( o_{\theta_i} \) grows with increasing \( \rho(a_i, S_k) \).

3.2.2. Likelihood. In emergencies, scenario probabilities can hardly be assessed adequately [29]. To develop an alternative measure for the relative likelihood of a scenario on the basis of the available information, a reliability assessment has been developed [3]. The reliability \( \xi(S_k) \) of \( S_k \) characterises the relative uncertainty of scenario \( S_k \) compared to the reliability of all other scenarios in \( S \). The reliability assessment requires information about the structure of the scenario (in terms of the number of uncertain variables and their dependence), and information about the uncertainty of individual pieces of information. The latter is usually only available locally, and should be determined by the experts providing the information. To facilitate local probability judgements, probability bounds are used [30]. Particularly, experts can specify that they cannot assess the likelihood of an event. Details on how the reliability is determined are described in [4].

As the flexibility of an alternative is more important the more uncertainty there is, \( o_{\theta_i} \) grows with decreasing reliability \( \xi(S_k) \).

3.2.3. Value of flexibility and evaluation of alternatives. There are numerous ways of combining \( \xi(S_k) \) and \( p(a_i, S_k) \) to a weight \( o_{\theta_i} \) such that the flexibility fulfils the properties with respect to severity and likelihood as described in 3.2.1 and 3.2.2. For the ease of use and transparency of application, a linear combination of both components is used here: \( o_{\theta_i} = \lambda \rho(a_i, S_k) + (1-\lambda) (1-\xi(S_k)) \). Using these weights, \( \varphi(a_i) \) can be determined as described in eq. (1) and (2). In this manner, a ranking of alternatives with respect to the value of their flexibility is achieved.

The flexibility itself should be interpreted as a relative measure enabling choosing the alternative that can still be adapted if adverse events or unforeseen developments occur. A flexibility of 0 means that \( a_i \) prohibits the implementation of any other alternative, a flexibility of 1 means that the set of feasible alternatives is not affected by \( a_i \). By using the scenario-based approach, the flexibility assessment integrates different developments and the associated importance of being able to revise a decision. Hence, an alternative with a high evaluation of flexibility should be favoured.

3.3 Example application

The alternatives investigated for dec 1 (population protection) are:

- evac: evacuation of area \( A_1 \) (close to the pipeline) and sheltering of \( A_2 \); rapid evacuation requires that most resources are dedicated to evacuation
- shelf: sheltering of area \( A_1 \);
- no effort: neither evacuation nor sheltering.

Figure 2 shows that the feasibility of the respective alternatives depends on the explosion of the pipeline, the infrastructure destruction associated to the potential explosion, the staff available and the population present. The constraints for the feasibility concern the staff (required vs. available), the irreversibility of evacuation, and a decision rule in case of explosion: if the destruction severely threatens the safety of the population, one of the evacuation options must be implemented.

The evaluation of alternatives depends on the information available. If dec 1 is assessed in an isolated manner, no information is available about the likelihood of the explosion or the impact of the use of resources on the feasibility of options regarding the leak. The local experts working on dec 2 can, however, specify bounds for the probability of the explosion and the repair of the leak in a given time both depending on the effort dedicated to the repair of the leak (cf. Figure 2, alternatives for dec 2 are major, minor and no effort). Additionally, if an explosion occurs, the work on the pipeline is stopped, and only resumed when the situation is considered stable. Respecting the staff constraints and further decision rules elicited from experts, the number of feasible options for each explosion scenario is summarised in Table 1.
Table 1: Number of feasible alternatives for explosion scenarios

<table>
<thead>
<tr>
<th>alternative decision 1</th>
<th>explosion</th>
<th># feas. alt. dec. 1</th>
<th># feas. alt. dec. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>evac rapid</td>
<td>yes</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>evac</td>
<td>yes</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>sheltering</td>
<td>yes</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>no effort</td>
<td>no</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

To determine the regret, the variables population presence, staff and infrastructure destruction are used (see Figure 2). By following the indicator approach described in [22], the respective values are normalised and aggregated depending on their influence on the attributes. Here, a distinction between high (bold arcs in Figure 2) and low influence is made.

By combining this information, the value of flexibility can be calculated. Figure 3 highlights the differences between an assessment of dec 1 individually and a combined assessment of dec 1&2. The overall value of flexibility decreases if information about dec 2 is taken into account. This is due to the fact the reliability of the scenarios increases when more information is available. The rapid evacuation is in both cases the least flexible option, as it forecloses most other options to be implemented. Sheltering is the most flexible alternative, because it enables implementation of both evacuation options and only makes limited use of resources. For evacuation and do nothing, the ranking changes between dec 1 and dec 1&2. This is due to the fact that do nothing is very flexible if no explosion occurs (cf. Table 1), as all other options can still be implemented. The reliability of the no explosion scenarios grows when information about dec 2 is taken into account, and the consequences of the more uncertain explosion scenarios gain in importance.

It is important that the flexibility is understood as a relative measure designed to compare different options rather than providing absolute numbers. In this manner, it can be helpful to revise standard practises and to test current plans with respect to the scenario-based what-if thinking without requiring the time and effort used in scenario-based approaches (see next section). The example has highlighted the importance of combining all on-going decision processes in the assessment. This is particularly important in situations of stress and time pressure, when information sharing and processing is accelerated and decision makers filter and reduce the information they process [36]. Here, the use of ICT systems and workflows that are configured at runtime to establish communication between the decision makers can be particularly useful. Additionally, intermediate information (such as the VoC) can provide useful insights in which information is important and should be gathered as soon as possible. Thus, the flexibility assessment is helpful in the early phases of an emergency, when reliable information is scarce and time is short.

4. Robust sequential decisions

When more information is available, and there is some time to make the decision, the strategies (sequences of decisions) can be evaluated in more detail. This section presents an approach that enables the decision makers to assess the consequences of a strategy under varying situation developments (scenarios). To keep the workload manageable and to integrate the best information available, ICT systems are used to integrate the locally available information. In this manner, the scenario construction does not require a complete enumeration of all possibly relevant events a priori.

To represent the timing of a decision, each single alternative is understood as a tuple $d_i = \langle a_i, t_i \rangle$, where $a_i$ is the measure that is implemented at time $t_i$. Strategies are (time-)ordered sets of these tuples.

4.1. Sequential decisions

4.1.1 Scenario-based sequential decisions. The basic idea for scenario-based SDM is to determine dynamically adaptable scenarios. To this end, the adaptability of the DAGs and the information about the relations between the variables (analogous to the flexibility assessment, cf. Section 3.2) are exploited.
The scenario construction is dynamic in the sense that (local) experts determine successively which alternatives can be implemented in a time step \( t_i \) respecting physical and organisational constraints. Again, the use of ICT systems is crucial to gather, share and process the information.

For each time step, the set of feasible alternatives to be investigated, the DAG (describing the interdependencies between variables), the information about the situation (values of variables), the preferences and the evaluations are updated for all strategies. The feasibility of alternatives is analysed as described in Section 3.1. By updating the constraints at each time step, it can be assumed that the feasibility of \( a_{i,j} \) only depends on the situation in \( t_i \) and potentially new information in \( t_{i+1} \) (i.e., a Markov property can be assumed). For instance, in case of scarce resources (constraints for \([t_0, t_1]\)), in each step \( t_i \) (\( i \in \{0, T\} \)) the resources spent in \((t_{i-1}, t_i]\) are subtracted from the overall resources available.

Having determined the feasible strategies, updated the constraints, and analysed the interdependencies of measures, SDM can, in essence, be understood as an extension of scenario updating. Starting at a time \( t_0 \), for each feasible alternative \( a_i \), a set of scenarios is generated and evaluated (as detailed Section 2.2). By exploiting the structural information about the workflows, efficient scenario updating is enabled: only the branches of the DAG that are (sufficiently) influenced by the new information need to be re-assessed. Values that are still considered as valid (in the sense that a change in their value as indicated does not have major consequences on the ranking of alternatives) can be re-used and adopted from the scenarios in \( t_i \). By making the trade-offs between the effort associated to the scenario construction and the need for timely available information explicit, it can be ensured that the information is available in due time while respecting the local constraints from contributing to the scenario construction [3].

4.1.2 Managing complexity. One of the most important problems in SDM is the complexity: the number of alternatives and the possibilities to combine them to strategies are overwhelmingly large. This is particularly true when temporal aspects are considered. Additionally, the events that may have an impact on the strategies’ consequences and their interdependencies need to be considered, increasing the complexity further. Therefore, approaches to curb the combinatorial explosion and keep the information manageable need to be implemented.

To avoid various overlapping or redundant scenario updating processes, the time steps \([t_0, t_{i+1}]\) are not fixed but adapted dynamically according to the alternative chosen, the occurrence of relevant events and the availability of new information. If the implementation of alternative \( a_i \) starts at \( t_i \), time \( t_{i+1} \) is the instance, when the application of \( a_i \) is finished, or it marks an event that prevents \( a_i \)’s further application. In both cases, \([t_i, t_{i+1}]\) represents the time of \( a_i \)’s execution. If multiple measures are applied simultaneously, \( t_{i+1} \) is the instance, when at least one of the measures cannot be executed any more.

Having established the rationale to specify the time steps, the alternatives need to be combined to strategies. To manage the associated combinatorics, the single measures, which constitute the strategies, are grouped to classes of similar measures that share equal or similar constraints with respect to their feasibility. To establish these groups, indicator based approaches are used. These approaches make use of the feasibility DAGs presented in Section 3.1, which enable the identification of the variables that may hamper the feasibility of an alternative.

Particularly, the measures are distinguished by the influence they exert on the set of feasible alternatives, e.g., evacuation eliminates the possibility of sheltering or do nothing in the subsequent time steps. If additional or auxiliary measures in the next or one of the future steps are required, this is captured in the set of mandatory measures (e.g., re-location of the evacuated population). Mechanisms to ensure that these measures are part of the respective strategies are implemented. Based on the sets of feasible and mandatory alternatives, a first (coarse) classification is derived. To derive a more fine-grained clustering, the alternatives that share a common relation towards a chance event (e.g., not possible if explosion occurs) are grouped and processed together. The process of strategy definition is finished when either the maximum time horizon \( T \) is reached or when the set of feasible alternatives is empty.

The above procedure can not only be applied to define strategies concerning isolated decision problems, but also for intertwined decisions. Again, to curb the combinatorics for decisions that are only interrelated with respect to their feasibility (and do not have an impact on the respective evaluation) only non-dominated strategies, which are favoured in at least one scenario, are investigated. More precisely, an alternative \( a_i \) in is non-dominated if there is no alternative \( a_j \) for which \( p(a_i, S_k) \geq p(a_j, S_k) \) for all \( S_k \) in \( S \).

4.1.3. Evaluation of strategies. The scenarios show for each strategy how its consequences may unfold over time. To evaluate strategies, it is important to establish the scope of the analysis, i.e., the period \([t, T]\). Per scenario \( S_k \) and alternative \( a_i \), however, the relevant time horizon \([t_0, T]\) (cf. Section 4.1.2) may vary, as in some scenarios, the situation may be resolved faster than for others, where important longer
term consequences are important. To ensure the comparability of strategies, the basis for the evaluation are the consequences over the maximum time horizon, i.e., on chooses \( t = \max_i t^i \).

By using the attribute tree, each scenario is evaluated at each time step \( t_i \) on the basis of preferential information. Usually, however, the preferences are not stable over time [1], and most theories of inter-temporal decision making suggest either specific time discounting methods or require the decision makers to correctly predict how their preferences will change over time [34]. While the latter approaches are very demanding, the first neglect the definition of risk as a function of probability and impact or undesired consequences [34, 35]. Therefore, here a different approach is followed: decisions are based on a comparison of evaluations over time, each associated to a particular course of events (cf. Figure 4).

For long term consequences a set of preferential scenarios is investigated reflecting the uncertainty about future preferences. The preferences can be elicited directly from the decision makers, or they can be modelled as a function of the scenario reliability and the severity of consequences. In this manner, strategies can be evaluated over time without neglecting the future potential consequences of a decision.

4.2 Example application

This section resumes the example from Section 3.3. After applying sheltering as a basis for further steps, more time is available, and the scenario-based SDM approach can be applied.

4.2.1. Alternatives to be evaluated. As the decision problems are only related via their feasibility (there are no attributes that are relevant for both dec 1 and 2), it is sufficient to consider the non-dominated strategies per decision problem. For dec 1, there are no dominated alternatives, whereas for dec 2, the evaluations show that as much effort as possible should be dedicated to the leak reparation in the first phases of the strategy. Therefore, only strategies that start with maximum resources for dec 2 are considered as building blocks for the construction of the strategy addressing dec 1&2. To ensure that all considered strategies are valid, the decision rules as given in Table 1 need to be respected. Finally, maintain sheltering refers to not changing the status quo, which is currently sheltering of area \( A_1 \). The option sheltering refers to an extension of sheltering in both areas \( A_1 \) and \( A_2 \).

4.2.2. Evaluation over time. Figure 4 shows a set of potential consequences for admissible strategies starting with “maintain sheltering” (dec 1) and “major effort” (dec 2). The evaluations depend to a large extent on the questions if the leak can be repaired in short time and if an explosion occurs. For the explosion scenarios, “maintain sheltering” results in a sharp decline of the evaluation (due to the immediate health consequences), and in a bad rating of medium and longer term impact (in part due to the longer time until staff is available and the associated health consequences as well as the mistrust and severe socio-economic consequences).

4.2.3. Overall evaluation. Although the results of the strategy maintaining the status quo are among the best in the no explosion scenarios, the devastating consequences of the explosion result in an unfavourable overall result. Figure 5 shows that evacuation combined with a major effort to repair the leak is the favoured option. This result is partly due to the high risk aversion of the decision makers who contributed to this example. As evacuation and sheltering alternatives are rated very similarly, the risk aversion and the preferences of the decision makers could, if time allows, be further investigated by using sensitivity analyses until a consensus can be found.

The example illustrated the application scenario-based SDM, which enables comparisons of different paths of developments instead of time-discounted values. By using the severity of the impact as a basis for determining the scenario weights [4], the consequence dimension of risk can be even more enhanced, and trade-offs between likelihood and consequence considerations are made transparent. The feasibility of this approach depends on the time availa-
ble, the experts providing input to the system and the willingness to share information across organisations. Additionally, it is important that the results derived should not be understood as prescriptive orders. Rather, they provide a meaning to facilitate communication, challenge current practices and plans and iteratively developing better strategies.

5. Conclusions

This paper supports decision makers in making robust decisions that remain feasible and are sufficiently close to desired developments for a variety of scenarios. To this end, temporal aspects and interdependencies across organisations are integrated. In this manner, potential conflicts of interest can be detected and, ideally, resolved such instead of local (intra-organisational) optima, robust and flexible inter-organisational strategies can be pursued. The integration of the temporal dimension enables considering several paths of developments and integrating the question when an alternative should be implemented and how long its execution takes into the evaluation process.

The formalisation of scenarios is exploited to detect overlaps of the related DAGs which represent interdependencies between decisions. In this manner, situation awareness can be enhanced, and communication between organisations can be facilitated by making the consequences of a decision in terms of further decisions transparent. Future research should address the question of the hierarchical levels: it is likely that decisions on a higher level are required to outrank decisions made on a lower level.

Beyond making dependencies explicit, this paper describes two approaches supporting decision makers in evaluating emergency management strategies: sequences of alternatives that are implemented at a specific time. Which approach to choose, depends on the information, resources and time available.

When time is critical, methods supporting near real-time decision making should be chosen. In these situations, information is typically incomplete, yet, pressure to implement first relief measures is high. In these situations the evaluation of alternatives can be based on the value of flexibility. The flexibility describes essentially in how far the decision to implement an alternative limits future options. The question how important the flexibility is (as compared to the evaluation of an alternative) is taken into account by analysing the importance of uncertainty and the severity of consequences if developments are unfavourable. This includes particularly the question if it is better to make a decision at present or if it is better to postpone the ultimate it until more information is available. In this manner, alternatives can be chosen that do not only address the immediate consequences, but provide a solid basis for relief and recovery.

In the later phases of an emergency typically more information is available, time is less critical and models that are targeted at building consensus between different actors can be used. The scenario-based approach to Sequential Decision Making (SDM) enables decision makers to explore and evaluate the possible developments of the consequences of a strategy. In this manner, weaknesses can be unveiled, and better strategies can be developed.

By exploiting the information in the scenarios and using the efficient scenario updating procedure, the scenarios can be constructed dynamically, referring to local expertise and taking into account the best available information as soon as possible. The plethora of possible strategies cannot be fully investigated given restrictions in time and resources. Mechanisms to cluster alternatives to groups that show similar behaviour and enable modelling relationships between the groups of alternatives (instead of single alternatives) are implemented to control the combinatorics while enabling the space of possible solutions to be explored thoroughly.

Throughout the paper it has been emphasized that the use of both approaches depends on the access to information from various sources and the quality of this information. While modern ICT systems facilitate access to information [11], the realisation of the system requires that experts register to the system, and provide the information they agreed to determine to their very best knowledge. A topic for future research is problem of manipulated information. The risk associated with postponing the decision vs. the risk of making the decision on the basis of potentially flawed information is to be addressed.

Both approaches are targeted at facilitating communication and supporting decision makers to achieve a common understanding of the situation and build consensus. To this end, results must be presented in a clear and understandable manner. This paper has shown few sketches to illustrate potential applications and to highlight the results. For application in practice, visualisations and complementary reports that facilitate the analysis must be developed for each specific group of users addressing their requirements and designed for the specific devices used. These visualisations are also an important stepping stone to further evaluations and tests with practitioners.

6. References