Efficient Scenario Updating in Emergency Management

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ABSTRACT

Emergency managers need to assess, combine and process large volumes of information with varying degrees of (un)certainty. To keep track of the uncertainties and to facilitate gaining an understanding of the situation, the information is combined into scenarios: stories about the situation and its development. As the situation evolves, typically more information becomes available and already acknowledged information is changed or revised. Meanwhile, decision-makers need to keep track of the scenarios including an assessment whether the information constituting the scenario is still valid and relevant for their purposes. Standard techniques to support scenario updating usually involve complete scenario re-construction. This is far too time-consuming in emergency management. Our approach uses a graph theoretical scenario formalisation to enable *efficient* scenario updating. MCDA techniques are employed to decide whether information changes are sufficiently important to warrant scenario updating. A brief analysis of the use-case demonstrates a large gain in efficiency.

Keywords

Scenario-based reasoning, situation awareness, multi-criteria decision support, scenario management and update

INTRODUCTION

Emergency situations are characterized by their complexity and the heterogeneity of the available information (Mendonca, Vieira and Sousa, 2007). To implement adequate mitigation measures, emergency managers must make sense of the situation, although information may be lacking, uncertain or conflicting (Van der Walle and Turoff, 2008). Additionally, emergency managers are confronted with redundant or irrelevant information causing information overload (Schaafstal, Johnston and Oser, 2001). Moreover, the situation itself and the information about it evolve dynamically: as time passes, new or more precise information may become available, whereas some already acknowledged pieces of information are confirmed or proven to be false.

Scenarios, which describe the situation and how it may develop, support emergency managers in gaining situation awareness (Endsley, 1995; Wright, Cairns and Goodwin, 2009). Scenario-based decision-making usually is supposed to start with the scenarios' conceptualisation and to end with the usage of scenarios for decision support (Huss, 1988). The intermediate stages are scenario planning, development, simulation, analysis and evaluation (Schoemaker, 1993). In this concept, scenario updating, i.e. accounting for and integrating newly available information requires a complete re-construction of the scenarios (Ahmed, Sundaram and Piramuthu, 2010). This is clearly infeasible in emergency situations, when time is bounded, and the availability of the experts contributing to the scenarios is limited.

To support emergency managers, we present a well-structured and efficient approach for handling newly incoming or updated information to ensure valid, reliable and manageable scenario-based situation assessment. This approach is efficient with respect to three aspects. First, it considers the *effort* needed to update the scenario. In this manner, time and resource constraints can be taken into account, and the feasibility of an update can be assessed, and impracticable scenario updates can be excluded. Secondly, a *relevance* assessment for the new information is introduced. This assessment answers the question whether the updated information is – given the emergency managers' preferences – sufficiently important to justify the effort of an update. Thirdly, if an update is required, the effort is reduced by enabling still valid information to be re-used and updating only those branches of the scenario that are affected by the new information.

The scenario updating mechanisms have been researched together with practitioners from emergency management (EM) authorities and applied to a use-case. In this use-case, a train wagon containing chlorine is damaged, setting off a chain of events that requires public safety personnel to assess the developing situation and take multiple possible future developments into account. This use-case is further explained and used throughout this paper to illustrate the impact of our efficient scenario updating mechanisms.

This paper first describes our approach to distributed scenario-based sense-making in dynamic situations such as those encountered in EM. This includes the definition of scenarios and their use for sense- and decision-making, the description of scenario construction, and the management of the construction process. The paper then describes the main challenges for using scenarios in dynamic environments; setting the stage for the description of scenario updates. The efficient scenario update method is based on two decisions: assessing the effort for updating scenarios and assessing the relevance of new information (to justify scenario updates). The use-case provides a running example showcasing the efficient scenario update method and substantiating the gain in efficiency. The paper concludes with a brief summary and an outlook on additional research topics.

DISTRIBUTED SCENARIO-BASED SENSE-MAKING IN EMERGENCY MANAGEMENT

Emergency managers need to make decisions, often with important consequences, despite stress and time pressure. Decision-makers react with habitual responses or well-learned behaviours in these circumstances (Plotnick and Turroff, 2009; Staw, Sandelands and Dutton, 1981). If the emergency situation is unprecedented or different from training cases, the resulting decisions may be ineffective or cause further harm. In these situations it is important that emergency managers are provided all relevant information in order to assess the situation and to make well-founded rational decisions (Plotnick and Turoff, 2009; Van der Walle and Turoff, 2008). Hence, the need for well-structured support providing and presenting the relevant information in an adequate manner arises.

Typically, emergency managers need to collaborate within emerging organisations-of-organisations. Therefore, sense-making is of particular importance. The basic idea of sense-making is that the perception of reality is an ongoing process that emerges from efforts to create order and to make retrospective sense of what occurs (Weick, 1993). As the situation evolves, information is typically updated and new information becomes available. Reasons for updates (of already existing information) may be that experts have been able to perform measurements or to use more sophisticated models requiring more time than their original assessment. Furthermore, additional experts may join the EM process, providing further information. Altogether, emergency managers are confronted with information updates that comprise changes of existing information, the availability of additional or the retraction of outdated information, as well as an update on the meta-information, e.g., about the uncertainty of the provided information. Due to this dynamic evolution, the implemented mitigation measures often need to be quickly re-assessed and eventually even be adapted or re-planned (Shen and Shaw, 2004).

Requirements for gaining situation awareness in EM comprise the participation of experts from different domains (Pavlin, Kamermans and Scafes, 2010). To avoid the problem of information overload (Fiedrich and Burghardt, 2007) it is important that only relevant information is processed and distributed. Additionally, constraints in terms of expert availability and limited time need to be respected. To provide support to emergency managers, the individual pieces of information must be combined and processed into meaningful and easily understandable descriptions (Comes, Conrado, Hiete, Kamermans, Pavlin and Wijngaards, 2010). To avoid cognitive biases such as overconfidence or the availability bias (Kahneman, Slovic and Tversky, 1982), it is important that the situation assessment conveys the (un-)certainty associated to the analyses.

To provide support in these situations, we propose following a distributed scenario construction procedure (Comes, Hiete, Wijngaards and Schultmann, 2011). The first step in this procedure is the elicitation of the decision makers' information needs: which information is required to gain situation awareness? These information needs are represented by a set of typed variables $\mathrm{FOCUS}=\{tv^F_1,\ldots, tv^F_n\}$, where each tv^F_i contains information of a specific type (e.g., text, .jpeg, mp3, symbol). The use of FOCUS enables filtering of information: only information *relevant* to determine at least one of the focus variables is considered. To discover the relevant variables and their interdependencies, a distributed approach based on the resolution of task dependencies is used, which lets experts (humans and automated systems) define their capabilities in terms of a task they can perform and information they require to this end (Pavlin et al., 2010). To provide this additional information, the system identifies and connects the experts via *software agents* (Pavlin et al., 2010): this achieves a loosely coupled distributed systems, which is orchestrated (via workflows) to jointly work on a problem at hand. In this manner, a network of experts collaborating to generate scenarios arises (Comes et al., 2010).

This network of dependencies among variables (specified by the experts) can be represented by a directed acyclic graph (DAG), which enables distributed information processing and scenario construction (Comes et al., 2010; 2011). To this end, the information is processed in a bottom-up manner following the directed links in the DAG. Each expert uses his local knowledge and procedures to determine the possible state(s) of the variable tv_j, for which he agreed to provide results given the information he receives. If there is uncertainty about the value $V(tv_j)$, an expert can pass on several possible estimates $V_1(tv_j)$,..., $V_n(tv_j)$ per variable. Therefore, the number of scenarios grows with growing number of uncertain variables and growing number of values per uncertain variable. Per value V_i, the experts are also asked to provide an assessment of the likelihood that tv_j's value in fact will be $V_i(tv_j)$, which is represented by $status_i(tv_j)$. They are free to provide qualitative assessments (such as "highly unlikely"), probability bounds, and estimates of probabilities or to declare that the value is certain. If they are not able to describe $status_i(tv_j)$, this ignorance is also denoted in the status by setting the probability bounds to 0 and 1 (Comes et al., 2011). On the whole, a scenario S_i can be understood as a tuple $S_i = \langle STV_i, sv_i, status_i, DI_i \rangle$, where STV_i denotes the set of relevant variables, sv_i contains one value per variable in STV_i, $status_i$ specifies the according status, and DI_i represents the interdependency structure (i.e., directed links) of the DAG for S_i. Note that FOCUS $\subseteq STV_i$.

This distributed approach in which experts define their task capabilities ensures that the experts are provided with the very information they have judged necessary to provide their service. In this manner, the problem of information overload, which includes the provision of irrelevant or redundant information (Gonzalez and Bharosa, 2009), is reduced. Another important requirement for situation awareness, information *consistency*, is ensured from the beginning onwards, under the assumption that the local assessments of the experts reflect the "state of the art" as good as possible, given their current knowledge and the available time (Comes et al., 2010). Moreover, the scenarios are *coherent*, as not only the variables' values are presented to the emergency managers, but the representation as a DAG describes their interdependencies. This coherence fosters transparency and provides an overview on (information) dependencies.

As the scenarios need to be tailored to the emergency managers' needs, it is important to trace and steer scenario construction in a manner that ensures that all requirements are met as good as possible. To this end, the distributed scenario construction is combined with a (decision-centric) scenario management component. Particularly, this allows the (potential) combinatorial explosion to be managed and ensures that a set of scenarios can be generated in due time whilst respecting the experts' (local) constraints and requirements.

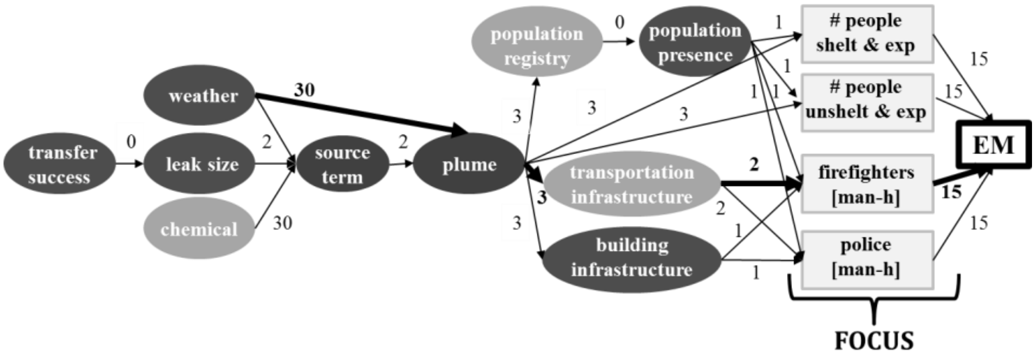

Figure 1: Configuration of expert network for the illustrative example

Figure 1 shows the arising network for the EM example. The FOCUS variables can be found on the right; further relevant variables are shown as ovals. Variables, about whose assessment there is (inherent) uncertainty, leading to an increase of the number of scenarios, are represented in black.

Table 1 shows a subset of (complete) scenarios (S1 to S9) constructed to gain situation awareness for the EM use-case, using the network as shown in Figure 1. The variables with a star (*) denote the uncertain variables that are shown to take multiple values. The other variables are certain, yet may differ in the certain value, given values of other variables in 'their scenario' that these depend on. Table 1 makes explicit that a variable's value is not necessarily a number. The only requirement for the types of value that an expert provides is that it should be possible to transmit it electronically and that it must be understood by the direct next experts in the DAG (connected with exactly one edge). Beyond providing an estimate of each variable, each expert also assess the maximal *duration* (in minutes) of providing an estimate using his currently preferred technique, rationale or model (line 2 in Table 1). Additionally, the effort (line 3 in Table 1) is a means for experts to specify their current workload. The effort is assessed on a qualitative scale, where 1 corresponds to "moderate", 2 to "busy" and 3 to "overloaded". The experts indicating that they are "overloaded" are asked to specify the number of scenarios they can at most process within a given timeframe. Here, the experts for the FOCUS variables *# pp shelt & exp*, *# pp unshelt & exp* and *firefighters* indicate that they can at most handle five scenarios in two hours, whereas the expert on *police* states that he can at most handle four in the same time (not shown in the table).

Table 1: Scenarios for Example use case.

scenario	variables							indicators			FOCUS			
	transfer success*	weather	leak size*	chemical	source term*	plume*	population registry	**population presence***	**transportation infrastructure**	**building infrastructure***	# pp shelt & exp	# pp unshelt & exp	firefighters [manh]	police [manh]
duration [min]	0	30	2	30	2	3	0	1	2	1	15	15	15	15
effort (1-3)	1	2	1	2	1	1	1	1	1	1	3	3	3	3
S_1	1	NW	none	Cl	none	none	0	0	none	none	0	0	0	0
S_2	0	NW	large	Cl	Big	Area-big-1	2500	2000	road works	standard	300	200	800	250
S_3	0	NW	large	Cl	Big	Area-big-1	2500	2000	road works	some dilapidated	500	200	850	300
S_4	0	NW	large	Cl	Big	Area-big-2	2000	1750	standard	standard	400	400	400	160
S_5	0	NW	large	Cl	Big	Area-big-2	2000	1750	standard	some dilapidated	700	400	450	180
S_6	0	NW	large	Cl	Medium	Area-med-1	1500	1100	standard	standard	800	300	160	80
S_7	0	NW	large	Cl	Medium	Area-med-1	1500	1100	standard	some dilapidated	500	600	250	100
S_8	0	NW	large	Cl	Medium	Area-med-2	1500	1600	standard	standard	850	750	250	125
S_9	0	NW	large	Cl	Medium	Area-med-2	1500	1600	standard	some dilapidated	750	350	340	140

On the basis of Figure 1, the longest path from a source to a sink node can be calculated to assess an upper bound for the duration of the scenario construction process (per scenario). In Figure 1, the edges are annotated with the respective *durations*, and the longest path connecting Weather to the Emergency Managers has a length (or duration) of 50 (minutes). For the effort, the maximum operator is used, as it is assumed that over-loading experts should be avoided, and that the path is only as good as the weakest (or most overloaded) link. In this example, all paths that include one of the focus variables are assigned the same effort (namely, 3). The above set of scenarios is the base-line for our further considerations on efficient scenario updating.

INDICATOR ASSESSMENT

To facilitate the assessment of partial and complete scenarios, an indicator framework is used, where the set $Ind_i \subset STV_i$ is a subset of the variables in the scenario. Each indicator is, via the DAG, causally connected to one or more FOCUS variables; all indicators are together connected to all FOCUS variables. The indicators are chosen such that differences in their values are a reliable *indicator* for differences in values of FOCUS variables. Hence, partial scenarios (i.e., the scenarios, for which the FOCUS variables' values are not all known), can be assessed regarding their relevance with respect to different FOCUS variables' values. In Table 1, the indicator variables which allow for drawing conclusions on the FOCUS variables are highlighted in grey.

Table 2: Indicator assessment for basic scenario set

indicator	scenario									indicator weight
	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	
building infrastructure*	1,00	0,50	0,00	0,50	0,00	0,50	0,00	0,50	0,00	0,25
transportation infrastructure	1,00	0,00	0,00	0,50	0,50	0,50	0,50	0,50	0,50	0,25
population presence*	1,00	0,00	0,00	0,13	0,13	0,45	0,45	0,20	0,20	0,50
indicator assessment	**0,00**	**0,88**	**1,00**	**0,69**	**0,81**	**0,53**	**0,65**	**0,65**	**0,78**	

To make comparisons across indicators that are typically measured on different scales each indicator is mapped by means of a value function onto a value in [0,1], where, corresponding to approaches of Multi-Attribute Value Theory, 0 signifies the worst value, and 1 the best (Keeney, 1996). To determine these value functions, the direction of influence of the indicator on the focus variables is determined (increasing or decreasing) and for each focus variable, it is determined if the according preferences are decreasing (i.e., a low value is preferred, e.g, manh, man hours) or increasing (e.g., health). By multiplying the respective assignments (each represented by +1 or -1), one determines the overall direction for the indicator. Next, the shapes of the value functions need to be determined. Here, we assume linear functions, methods how to derive further shapes have been explained by von Winterfeldt and Edwards (1986). Subsequently, the indicator values' assessments are aggregated into a single value. For its transparency and ease of use, we use a weighted sum to aggregate the single assessments (cf. Stewart 1995). The importance of an indicator is derived from structural considerations. It is assumed that the more FOCUS variables an indicator influences, the more important this indicator it is. Hence, the weight of each indicator ind_i is calculated by summing the weights of FOCUS variables to which it is connected. As each indicator by definition has an impact on at least one FOCUS variable, each weight is greater than 0. Finally, a normalisation of weights is performed, to ensure that the sum of weights equals one. Table 2 specifies the indicator weights for the use-case where the underlying structure remains the same as in Figure 1.

USING SCENARIOS IN DYNAMIC ENVIRONMENTS

In EM, it is necessary to quickly gather, analyse, distribute and process information into meaningful descriptions of the incidents whilst keeping track of the dynamic evolution of the environment (Gonzalez and Bharosa, 2009; Plotnick and Turroff, 2009). As the present unfolds into the future, different or more accurate information about the incident becomes available (Mahmoud et al., 2009). The existing scenarios need to be reviewed and assessed to determine whether the currently implemented measures and strategies must be modified or changed. Hence, to ensure situation awareness reflecting the current knowledge about the situation best, continuous revisions and corrections of scenarios are necessary. The key issue is that the scenario updates are conducted in an *efficient* and *responsive* manner.

In literature, however, the problem of scenario updates is hardly systematically addressed. Usually, an update involves a complete reassessment of the scenarios (Mahmoud et al., 2009; Pascual, 1999). In the field of context awareness, Zhu, Pung, Oliya and Wong (2011) recently published an approach that allows distributed experts to subscribe to information about whose updated values they need to be informed if these updates change the value more than a threshold value. This approach is, however, only of limited applicability in the field of EM. First, emergency situations are complex and prone to non-linear developments (Helbing, 2009). Therefore, a small change in a variable's value can have important consequences for further parts of the system. This causes the problem that although an event may seem negligible when viewed in isolation, it can have relevant consequences, and potential threats can be ignored (Adam, 2007). Second, in this approach each expert is free to choose if he would like to take into account the information or not. This may lead to inconsistent scenarios.

A scenario can be updated due to a change in its dependency structure (represented by the DAG), a change of a variable's value or its status. In the context of this paper, we focus on an update of values (or the likelihood assessment that a variable takes a value). The dependency structure (underlying DAG) can vary as well (e.g., as more complex networks can be applied when more time is available), but the DAG is assumed to be stable here for simplicity's sake. Efficient scenario updating has two aspects. First, it is necessary to assess if the new information is "relevant enough" to justify the updating effort. Both concepts (relevance and effort) are defined rigorously in the following section enabling the formulation of the updating decision in terms of a constrained 3-dimensional optimisation problem. Second, efficient updates allow for information to be reused that has already been assessed and that is still valid, while updating the pieces of information whose value has changed.

EFFICIENT SCENARIO UPDATES

As scenario updating is closely related to timing issues, from now on the scenario is be annotated with the time t when it was determined: $S_i = S^t_i = \langle STV_i , sv^t_i , status^t_i , DI_i \rangle$. ($STV_i$ and DI_i are assumed to be constant: the DAG is stable for these scenarios.) If an expert provides a new value at time $t+T$, $V^{t+T}_i(tv_j)$ for a variable $tv_j \in STV_i$, a decision must be made, if the scenarios S_i, which assumed $V_i(tv_j)= V^t_i(tv_j)$ need to be updated, resulting in the set of new scenarios SS^{new}. To this end, the new information's relevance is assessed. If the information is judged sufficiently important, an efficient update needs to be employed. The efficiency gain is illustrated later.

First and foremost, the effect of scenario updating is shown for the example use-case. After having completed the scenarios S_1 to S_9, shown in Table 1, the expert on the Source Term has invested time to make more accurate estimations on the outflow of the Chlorine, based on pictures of the actual hole sent by the local incident commander. The expert revokes the value "Big" (i.e., changes the status to 'irrelevant'), and replaces the value 'Medium' with two possible outflow rates: 4 kg/s and 5 kg/s. The result is that immediately scenarios $S_{2,3,4,5}$ are 'pruned'. Furthermore the resulting changes to scenarios S_6-S_9 are shown, where the white background scenarios *are not sufficiently different* to be actually continued (hence the 'no value') indication for the associated FOCUS variables (except for scenario S_9, for which these values were already determined, and no updating was necessary). The reasons for completing or not completing, new scenarios are described below.

Feasibility of Performing a Scenario Update

The update of information may concern both FOCUS complete and incomplete scenarios, in which there are variables that have not been assigned a value yet. The scenario recipients must balance the time (still) available for the purpose at hand; the time and effort necessary for that update along with the workload of the experts involved; and the (projected) effect of the new value(s) on the FOCUS variables. In case a full update of the scenarios cannot be accomplished (e.g., as some experts are hardly available, or as some assessments are too time consuming), a decision must be made whether: (a) the original (consistent) scenarios are retained as a basis for the purpose at hand, (b) a partial update (that may lead to inconsistencies) is performed by updating only those branches of the scenarios for which an update is feasible, or (c) the most relevant scenarios are selected for updating (including a recalculation of all values that are affected by the update).

For the assessment of the time and effort necessary to perform a value update, all steps within the scenario construction and analysis need to be respected. Therefore, the time and effort depends on the number of scenarios S_i in SS^{new} that need to be updated, the number of variables tv_j in each STV_i, whose value must be updated, and the effort and duration these updates require.

For our efficient scenario updating method we exploit the directed acyclic graph (DAG) representing the information within a scenario: standard graph analysis concepts are now available, including a *path*. For assessing the duration, each edge in the DAG is weighted with duration. To establish a bound for the maximum duration to conduct scenario updates, the longest paths between the modified variable and any FOCUS variable and the "bottleneck variables", whose assessment takes the longest, need to be determined. The sum of these annotations in a path provides the overall duration per path. Furthermore, the time for a complete update is larger or equal to the time for each single scenario update. This upper bound for the duration of scenario updating can be compared against the time remaining for the decision problem at hand taking into account time already spent on this part of the efficient scenario updating method. For constructing 8 new partial scenarios (assuming that the source term is already calculated): an upper bound of the duration is 5+8*15=125 min. (2:05). Note that scenarios are *not* constructed from scratch; we re-use values from the original scenarios. Assuming that the time available for the updates is 2 hours, it is clear that then at most seven scenarios can be updated. Additionally constraints given by the experts, who can become, or already are overloaded, need to be taken into account. For example, as the expert determining the variable *police manh* can at most process four scenarios in two hours, no more than 4 scenarios can be updated within the available time.

Information Relevance Assessment

Given enough time available to conduct scenario updating, the impact of the information update needs to be assessed with regard to FOCUS variables and their specific values. This impact assessment is achieved by *not* computing all complete scenarios based on the information update, but rather by using the indicator framework. For the updated information, we need to establish the (new) values only for the (causally related) indicators.

This means that a number of (new) partial scenarios *must* be constructed until the point that the values of the causally related indicator variables become known; the other values of the indicators can be 'copied' from the original scenarios. Our method thus re-uses values of variables that have not changed (based on the DAG structure), thereby avoiding unnecessary reassessment: only those variables that causally connect the updated variable with the indicator variable must be re-assessed. This minimal scenario updating effort must be spent, using a certain duration, to be able to assess the impact of the information update and whether some scenarios can be pruned (including 'old complete' scenarios and these new partial scenarios) and which of these new partial scenarios can be continued until they are complete(d).

Table 3: Updating scenarios S_1-S_9. Scenarios $S_{3,4,5}$ are pruned, white-background scenarios are not completed.

scenario	variables								indicators		FOCUS			
	transfer success*	weather	leak size*	chemical	source term*	plume*	population registry	transportation infrastructure	population presence*	building infrastructure*	# pp shelt & exp	# pp unshelt & exp	firefighters [manh]	police [manh]
duration [min]	0	30	2	30	4	3	0	1	2	1	15	15	15	15
effort (1-3)	1	2	1	2	3	1	1	1	1	1	3	3	3	3
S_1	1	NW	none	Cl	none	none	0	none	0	none	0	0	0	0
S'_{6a}	0	NW	large	Cl	4 kg/s	Area-med-1a	1500	standard	850	standard	600	250	160	100
S'_{6b}	0	NW	large	Cl	5 kg/s	Area-med-1b	1500	standard	1100	standard	-	-	-	-
S_6	0	NW	large	Cl	Medium	Area-med-1	1500	standard	1100	standard	800	300	160	80
S'_{7a}	0	NW	large	Cl	4 kg/s	Area-med-1a	1500	standard	950	some dilapidated	-	-	-	-
S'_{7b}	0	NW	large	Cl	5 kg/s	Area-med-1b	1500	standard	1050	some dilapidated	-	-	-	-
S_7	0	NW	large	Cl	Medium	Area-med-1	1500	standard	1000	some dilapidated	500	500	250	100
S'_{8a}	0	NW	large	Cl	4 kg/s	Area-med-2a	1500	standard	1500	standard	1000	500	250	120
S'_{8b}	0	NW	large	Cl	5 kg/s	Area-med-2b	1500	standard	1400	standard	-	-	-	-
S'_8	0	NW	large	Cl	Medium	Area-med-2	1500	standard	1600	standard	850	550	350	125
S'_{9a}	0	NW	large	Cl	4 kg/s	Area-med-2a	1500	standard	1700	some dilapidated	1000	700	350	120
S'_{9b}	0	NW	large	Cl	5 kg/s	Area-med-2b	1500	standard	1800	some dilapidated	950	750	400	120
S_9	0	NW	large	Cl	Medium	Area-med-2	1500	standard	1600	some dilapidated	750	350	340	140

The example in Table 3 and the DAG in Figure 1 show that the update of information on the *source term* causes a change in values for the indicator *population presence* via the variables *plume* and *population registry*. Scenarios S_2 to S_5 can be pruned immediately, as they assumed a *"Big"* source term, and therefore relied on wrong assumptions. Table 3 shows that the indicator *transportation infrastructure* is not significant any more: there are no differences in the values for all valid scenarios. Therefore, *transportation infrastructure* is deleted from the set of indicators. Moreover, Table 3 shows that these new values for the indicators (available in all updated partial scenarios) can be aggregated-compared against the *old* values of this indicator (in the original (complete) scenarios). Table 4 specifies the re-assessed weights for the remaining indicators.

Table 4: Indicator assessment for updated scenarios compared to original assessment

	updated scenario									indicator
updated indicator	S'_1	S'_{6a}	S'_{6b}	S'_{7a}	S'_{7b}	S'_{8a}	S'_{8b}	S'_{9a}	S'_{9b}	weight
population presence	1,00	0,58	0,45	0,53	0,38	0,25	0,30	0,15	0,10	0,67
building infrastructure	1,00	0,5	0,5	0	0	0,5	0,5	0	0	0,33
evaluation of indicator	1,00	0,45	0,53	0,65	0,75	0,67	0,63	0,90	0,93	
difference	**0,00**	**0,03**	**0,05**	**0,30**	**0,65**	**0,32**	**0,28**	**0,67**	**0,70**	
original evaluation of indicator	1,00	0,48		0,35		0,35		0,23		
	S_1	S_6		S_7		S_8		S_9		
	original scenario									

Table 4 shows the recalculated indicators and their difference with respect to the original evaluation of the indicator (see also see Table 2). In Table 4 the scenarios are highlighted in which the difference of the indicator is *large enough* to warrant further completion of the scenario and the other scenarios are not further completed.

Table 5: Complete scenarios for scenario S_6.

scenario	variables							indicators			FOCUS			
	transfer success*	weather	leak size*	chemical	**source term***	plume*	population registry	**population presence***	**transportation infrastructure**	**building infrastructure***	# pp shelt & exp	# pp unshelt & exp	firefighters [manh]	police [manh]
duration [min]	0	30	2	30	**4**	3	0	1	2	1	15	15	15	15
effort (1-3)	1	2	1	2	**3**	1	1	1	1	1	3	3	3	3
S'_{6a}	0	NW	large	Cl	**4 kg/s**	Area-med-1a	1500	standard	850	standard	600	250	160	100
S'_{6b}	0	NW	large	Cl	**5 kg/s**	Area-med-1b	1500	standard	1100	standard	800	300	160	100
S_6	0	NW	large	Cl	**Medium**	Area-med-1	1500	standard	1100	standard	800	300	160	80

The example in Table 5 shows (with all three scenarios completed for illustrative purposes), when e.g. looking at the scenarios S'_{6a} and S'_{6b}, which are 'new' scenarios related to scenario S_6, that scenario S'_{6b} is **not** different from scenario S_6 – for the value of the indicator 'Population Presence'. Hence, scenario S'_{6b} does not need to be continued, and the original scenario S_6 can be retained. However, scenario S'_{6a} is sufficiently different from scenario S_6 for this indicator, and warrants further construction into a complete scenario (shown in Table 3).

In sum, only those *new* partial scenarios are further constructed into complete scenarios, if the value of the indicator assessment is *sufficiently* different from the value of original assessment. In this manner, the indicator assessment can be interpreted as a similarity measure. The *threshold* for determining if the scenarios are "sufficiently diverse" to justify an update is currently set (per default, adjustable by the decision maker) at 0.05: below that value scenarios are 'sufficiently similar'. Furthermore, before completing any of these partial scenarios, the time and effort requirements need to be respected.

The amount of differences in values for the indicators is related to a ranking of feasible updates. This ranking takes into account the expected impact of the change in value of the indicator, the duration bounds and effort bounds. The ranking of feasible updates is determined via solving a constrained 3-dimensional optimisation problem, in which the feasible updates are considered the alternatives, and the goal function to be minimised has the three dimensions impact, duration and effort, where the preferences of the decision maker are elicited to indicate relative importance of these criteria (per default: minimum duration and minimum effort and maximum impact are preferred), see the call-out box below. The resulting ranking is used in, e.g., situations when limited time is available and a selection of partial scenarios for updating needs to be made.

Decision on Scenario Update Due to a Change of Value. Assume that new information on J independent variables $tv_{j1}, \ldots, tv_{jJ} \in \cap_{i \in I} STV_i$ is available. A decision must be made which of the values are updated. Below, only the update of single variables' values is investigated, to rank the most useful updates. This optimisation problem is defined as follows, where the updating of the variables tv_{jk} is denoted a_k, and not performing an update is denoted a_0:

$$w^1 v^1_D(x^1_k(a_j)) + w^2 v^2_D(x^2_k(a_j)) \rightarrow \max!$$

Subject to:

$$j = 0,\ldots,J$$
$$w_l \geq 0 \quad (l=1,2)$$
$$w^1 + w^2 = 1$$
$$dur(P^L_{i,tvj}) \leq T^{max}(P^{up}_{\omega}) - T^{analysis}$$

Here, $x^1_k(a_j)$ denotes the score of the duration of effort assessment (depending on the information available), while $x^2_k(a_j)$ denote the result of the impact assessment (depending on the purpose) for j=1,...J. For j=0 (i.e., the option of not performing any update), one defines $x^1_k(a_0)=x^2_k(a_0)=0$. v^1_D and v^2_D are the respective value functions modelling the decision makers' intra-criteria preferences. Here, the preferences for the effort are assumed to be decreasing (i.e., the lower the effort the better) while the preferences for the impact are supposed to be increasing (i.e., the bigger the difference, the more important it is to perform an update). The weights w^1, w^2 indicate the respective importance of the objectives. The duration of the value updated is expressed in terms of the paths (see main text), and is set against the time available for decision making minus the time needed for this analysis. In this manner, a ranking of feasible updates can be achieved.

Changes to the status of a value are also considered. E.g., direct pruning can be employed for the information update on the *Source Term*, where the value *Big* has now the status *irrelevant*. This immediately implies that all scenarios in which *Source Term* has the value *Big* can now be pruned: this is shown in Table 4 in which scenarios $S_{2,3,4,5}$ are pruned, and thus are not used for situation assessment or decision-making.

The description and example above describe the efficient scenario updating of *one* variable whereas our method is defined to handle efficient scenario updating for information updates of multiple variables. The formalization of our method is too lengthy to be described in this paper, but is described in detail in (Comes, 2011).

DISCUSSION

The impact of our efficient scenario update method can be easily shown by comparing it with complete scenario re-construction (as is often advocated, see above) using in both cases the same metrics for duration. The effort estimation is not present in the other approaches. The efficiency of our method is related to avoiding the re-assessment of information, which is still a sufficiently valid basis for the decision at hand. This includes making a decision if the updated information justifies the effort and duration of updating. If the latter question is answered positively, the graph theoretical formalisation facilitates re-using information that is not affected by an update. For instance, the update of the variable *Source Term* does not require that the experts providing information on the *Chemical* or the *Weather* need to provide their information again. This is different from discursive scenario construction techniques, where interrelations are *not* made explicit and experts from all relevant domains are brought together to construct the scenarios.

Furthermore by the careful construction of new partial scenarios up to the point that the relevant indicator variables obtain a (new) value, we can limit the re-assessment to only those of the partial scenarios that are considered to be sufficiently different with respect to the FOCUS variables. For ease of this comparison, we assume that both our efficient method as well as other methods immediately prune scenarios that have become obviously irrelevant because of the information update (cf. scenarios $S_{2,3,4,5}$ in our example). The example shown in Table 1 and Table 3 provides a means to exemplify this gain in efficiency:

- For complete re-assessment, 8 new scenarios are constructed ($S'_{6a\text{-}b}$, $S'_{7a\text{-}b}$, $S'_{8a\text{-}b}$ and $S'_{9a\text{-}b}$).
- With our efficient scenario updating method, 8 partial scenarios are constructed until the point that the indicator Population Presence has been given (new) values, re-using non-causally related values from their 'original' scenarios. The variables *Transfer Success, Weather, Leak Size* and *Chemical* remain unchanged and are adopted into the new scenarios. Then, out of these 8 new partial scenarios, only 4 are completed (S_{6a}, S_{8a} and $S_{9a\text{-}b}$).

This is further illustrated by a calculation of the duration spent, where we assume the duration as in Table 3.

- The longest path through the network has a length of 90 minutes, thus an upper bound for the duration of each scenario construction process is 1:30 h. As the longest process within the map takes at most 40 minutes, an upper bound for the total duration of scenario construction (assuming efficient and immediate processing of information) is 30+8*40+3+2+15=370 minutes (or 6:10 h) for complete re-assessment.
- For our efficient scenario updating, the duration spent is:
  - For constructing 8 new partial scenarios (assuming that the source term is already calculated): an upper bound of the duration is 5+8*15=125 min. (2:05). Note that scenarios are *not* constructed from scratch; we re-use values from the original scenarios.

- For completing the four selected scenarios: an upper bound of the duration 5+4*15=25 minutes.
- The total duration for efficient scenario updating is 2:05h + 0:25h = 2:30h.

The actual performance gain shown above is indicative only for this small example. In more complex situations, the performance gain depends on the variables, for which information is updated, the duration of this update, the structure of the DAG, the variables connecting the updated variables and the related indicators, the variables connecting the related indicators and focus variables, and the actual values produced by the involved experts, their actual time spent, and the differences of the indicator variables' values. Nevertheless, we can guarantee efficient updating given these constraints.

CONCLUSION

The challenge addressed in this paper is making sense of a dynamic situation while handling updates of information and respecting time and effort constraints. We have shown that our formalised and well-structured approach to scenario-based sense-making enables efficient scenario updates. The formal graph-based approach for scenario representation has the advantage that (direct and indirect) dependencies are made explicit. In this manner, *efficient* scenario updating is facilitated, as updating does not require a complete revision of all scenarios, but allows for adapting only the parts of the scenarios that are affected by the changed information.

Our solution includes an MCDA-based tool to assess the relevance of updated information, together with an estimation of the duration and effort required to conduct the prioritised scenario updates. By exploiting the DAG representation and the annotations provided by experts, graph theoretical techniques can be employed to derive bounds for duration and effort. This resolves the scenario updating decision problem to a constrained 3-dimensional optimisation problem. Furthermore, the use of a DAG facilitates the re-use of information that is unaffected by information updates and renders further efficiency gains possible. Our approach is substantiated by an implementation that accompanies a distributed system that constructs scenarios. Our efficient scenario updating method is available for further testing, and an additional method is being researched for updating scenarios due to changes in the structure of the underlying graph.

Our approach is strongly related to the quality of information on the network and the experts therein: the more knowledge available on the experts, and their reasoning (duration, effort and sensitivity to updates); the faster and more accurate the update decisions can be made, the more efficiency can be gained. Yet, scenario updating requires time and input from the experts involved. Usually, there is a trade-off between effort of the update (with respect to time and expertise required) and consistency (including value, status and observation consistency). This leads to another decision problem: the decision on which partial updates (i.e., only some of the scenarios are updated) to allow, while minimizing the potential inconsistencies that may arise (as now not all scenarios are based on updated information). This is one aspect of our continuing research. Furthermore, the generalizability to apply our approach in sense-making and decision-making tools is of interest.

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