A multi-stage scenario construction approach for critical infrastructure protection

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ABSTRACT

Protecting critical infrastructures (CIs) against external and internal risks in an increasingly uncertain environment is a major challenge. In this paper we present a generic multi-stage scenario construction approach that is applicable to a wide range of decision problems in the field of CI protection. Our approach combines scenario construction and decision support, whereby we explicitly consider the performance of decision options which have been determined for a set of initial scenarios. Because of the iterative character of our approach, consequences of decision options and information updates are evolutionary processed towards advanced scenarios. By disturbing vulnerable or critical parts of CIs, cascading effects between interrelated CIs and the responses to the decision options can be determined. We apply this scenario-construction technique to two civil security research projects. One focuses on protecting food supply chains against disruptions, whereas the other aims at securing public railway transport against terrorist attacks.

Keywords

Critical infrastructure protection, scenario-based decision support, iterative-dynamic scenario construction, uncertainty, complexity.

INTRODUCTION

Any infrastructure whose functionality is of essential importance for modern societies and whose failure or malfunction causes sustainable disturbances of economies and societies is called a critical infrastructure (CI). Of particular importance are, inter alia, electricity generation facilities, electric power grids, supply networks, transport systems and financial services (Abou El Kalam et al. 2009). The more complex and interdependent CIs become, the greater are the difficulties to protect them against internal and external risks in an increasingly uncertain environment. To reduce risks to CIs in Germany, the German federal government funds selected civil security research projects, such as SEAK and RIKOV. SEAK focuses on enhancing security and reliability of food supply chains (FSCs) whereas RIKOV aims at developing a holistic risk management approach to better protect public railway transport (PRT) systems against terrorist attacks. Both projects have in common that (i) the considered CIs are particularly complex, that (ii) they are characterized by a high degree of uncertainty and that (iii) strategic decisions are required. However, the projects differ on an essential aspect: SEAK deals with natural (or aleatory) threats whereas RIKOV considers threats that arise from intelligent adversaries (Hall 2009).

Strategic decisions provide the setting in which precise and rational decisions can be made, in our case ad-hoc and operational (SEAK) or proactive and tactical (RIKOV) decisions. Following the considerations of French et al. (2009), strategic decisions tend to be associated with unstructured or non-programmed problems. They intend to support decision-makers (DMs) to optimal prepare for or respond to anticipated and non-anticipated threat situations. In strategic decision situations, DMs usually have to cope with severe uncertainties because of either the long-term focus of the decisions or the complexity of the decision environment. As Flach (2012) explicitly highlights, uncertainty and complexity are highly interrelated. In this paper - corresponding to the common notion - complexity is directly related to the number of admissible possibilities within the problem space; more possibilities entail greater complexity of the decision problem (Flach 2012; Hollnagel 2012). A decision problem is referred to be complex if the number of possibilities cause uncertainty about the future and thus make it difficult to choose an optimal response strategy (Flach 2012).

Methods of operations research are useful when dealing with uncertainty and complexity in strategic decision situations. To integrate uncertainties into an optimization model, formal quantitative approaches such as explicit risk measures, probabilities, decision weights or fuzzy numbers are applicable (Durbach & Stewart 2012). These approaches require several assumptions about the likelihood of the upcoming information (Comes 2011; R. Lempert et al. 2002). However, scarcity or non-availability of information in complex situations often makes it difficult to apply these approaches. Alternatively, scenario techniques can be used to cope with uncertainties (Bunn & Salo 1993; Assavapokee et al. 2008). A scenario is a plausible, consistent and coherent description of a situation to explore various possible development paths and future states (Harries 2003; Comes 2011). Any set of scenarios should contain likely and unlikely future realities. Scenario planning is not about predicting the future but rather improving prediction, increasing creativity and enhancing understanding of causal links between key uncertainties (Harries 2003; Wright & Goodwin 2009).

Our paper aims at presenting a generic approach for end users (i.e. companies, authorities, ministries) to construct scenarios taking into account great uncertainties and complexity. This allows a better protection of different vulnerable parts of the considered CI by evolutionary integrating evolutionary both the consequences of decision options and information updates into scenarios. The remainder of this paper is organized as follows. In Section 2, the state of the art of scenario construction is briefly presented and specific requirements for scenarios that need to be fulfilled for CI protection are highlighted. Section 3 suggests a multi-stage scenario construction approach which is exemplarily applied in Section 4 for the protection of food supply chains and public railway transport systems as it is the scope of SEAK and RIKOV. The paper closes with a conclusion and discussion in Section 5.

SCENARIO CONSTRUCTION FOR FORECASTING UNDER UNCERTAINTY

Scenario construction for decision-making - a brief review

Since scenario construction techniques become more important to identify and highlight uncertainties in complex decision situations, a large variety of terms for scenario techniques exist, e.g. scenario thinking, scenario planning, scenario construction, scenario generation or scenario analysis (Bradfield et al. 2005). We follow the assumption that scenarios offer the possibility to consider future developments of a situation regardless their likelihood (Byman et al. 2000). A formal definition of a scenario is given by Hites et al. (2006) where a scenario s is understood as a vector in R^n which includes the values for n uncertain parameters. The i^{th} coordinate of the vector specifies the value for the i^{th} uncertain parameter. The quality of the scenarios used for decision-making has a high impact on the quality of the recommended decisions. To be a useful measure for decision-making, it is important for all scenario construction methods to provide challenging and structural different scenarios that are sound, consistent and plausible (Mietzner & Reger 2004). As it is impossible to capture the overall space of possible scenarios, the set of scenarios should rather encompass a small number of highly relevant scenarios. That requires an adequate scenario construction process (Stewart et al. 2013). A crucial challenge is the anticipation of unknown uncertainties to forecast possible developments (Montibeller et al. 2006).

There exist multiple scenario construction methods. Many of them develop scenarios in a descriptive story-like form. Wright & Goodwin (2009) apply scenario construction to develop a range of plausible futures as pen-pictures by focusing on key uncertainties and certainties. Comes et al. (2012) use story-like scenarios to follow up uncertainties and to achieve a deeper understanding of relevant interdependencies of a certain decision problem. Scenario construction is also possible using the Delphi method where experts' opinions are integrated. The method assumes that judgments of a group of experts are more valid than judgments from individuals (Linstone & Turoff 2002). According to Bañuls & Turoff (2011), key characteristics of the Delphi method are that the process is repetitive, maintains the participants' anonymity, provides controlled feedback and represents a group statistical response. Another way to construct scenarios is using scenario trees. This method is widely used for financial optimizations in terms of discrete approximations to a continuous distribution (Geyer et al. 2013). A fourth method to construct scenarios is asking 'what if?' questions to rehearse future states or developments. Asking these questions helps DMs to compare and evaluate different strategies and decisions. The above mentioned approaches deal exclusively with scenario construction. There exist, however, other approaches that, inter alia, solely focus on scenario updating. For more information see for instance Comes et al. (2012), where scenarios are updated by changing the dependency structure of the impact variables, their values and/or statuses.

Requirements for scenario construction to protect CIs

The protection of FSCs and PRT systems against risks are chosen as illustrative examples for the application of a scenario-based analysis in complex environments. In the first case, a decision support (DS) framework is developed that allows the analysis of scenarios by focusing on the disruptions of FSCs. The latter case carries out a scenario-based risk analysis to evaluate system vulnerabilities, threats and possible consequences of terrorist attacks. The crucial challenge with which scenarios have to cope within this field of research is the complex decision environment which is characterized by strong uncertainties (Flach 2012). Basically, uncertainties can be either epistemic or aleatoric. The former refers to a lack of knowledge or sparse information, whereas the latter copes with random effects (Senge et al. 2014). For instance, aleatoric uncertainties may include variations of unpredictable outcomes such as randomly changing wind speeds in the case of a natural threat or the motivation and capacity of an intelligent adversary. Epistemic uncertainties may refer to the state of the DM during a disaster where the decision environment is expected to be at least highly complex or even chaotic or the decisiveness of an intelligent adversary (depending on the opportunities to harm a system). The relevance of scenarios for CI protection requires the integration of both types of uncertainty.

In complex situations, it is impossible to identify sets of scenarios that contain all possible future developments of a situation and thus capture most uncertainties. To rather develop a set of scenarios including a representative sample of the total scenario space, random combinations of values and states for the uncertain parameters are typically selected, i.e. following the definition given in Hites et al. (2006). This causes, in turn, problems when the decision context is dynamic and rapidly faced by new information. Although scenarios offer the possibility to explore feasible and promising decision options out of the wide range of possible options, the results may be insufficient. This is because the exclusive focus on randomly varying values and states for unknown parameter uncertainties lead to limitations in the validity and consistency of the used scenario set. Decision options that may be relevant are neglected.

This paper presents a generic scenario construction approach where (consistent) scenarios are constructed in a process of dynamic interaction within the decision environment. Scenario construction then exceeds the exclusive focus on randomly generated or assumed values and states for uncertain parameters by additionally exploring dynamic variations of the decision environment. When decision options are verified under dynamic influences, more information about their weaknesses and advantages are revealed. The approach requires a tight coupling between scenario construction and the exploration of decision options. In fact, an evolutionary exploration of future developments is needed to identify decision options based on (1) "traditional" assumptions for scenarios that consider randomly varying values for uncertain parameters and to (2) investigate dynamic developments of a situation by, individually for all decision options, explicitly disturbing vulnerable and critical parts within the decision environment.

THE MULTI-STAGE EVOLUTION OF SCENARIOS BY INTEGRATING SECURITY-RELEVANT RESULTS

In this section we present a multi-stage (iteratively conductible two-stage) scenario construction approach which is useful for decision-making under uncertainty, with uncertainties captured by the number of scenarios. Instead of exclusively considering varying states and values for uncertain parameters within the scenarios, also specific decision options are taken into account. Thus, we take a new focus in different respect: the dynamics of and the developments within the decision environment as well as the responses to a specific decision option. The first stage of the approach is to determine initial scenarios. In the second stage, the initial scenarios are evaluated under the assumption of an evolving decision environment towards a vulnerable state or a state of failure. The rationale of our approach comprises three parts: qualitative and quantitative scenario construction and DS (see Figure 1). Note that the approach is the continuation of the work presented in Comes et al. (2013).

The approach encompasses two directions. First, decision options are identified based on a set of initial scenarios containing exogenous impact factors that are independent from possible decision options. The initial scenarios are in line with the definition given in Hites et al. (2006), where scenarios are understood as a combinational aggregation of values for impact factors to explore future developments of a status quo (see previous section). Second, based on the chosen decision options for the set of scenarios and the identified vulnerable and critical parts of the environment, these initial scenarios are further elaborated to advanced scenarios. It requires a tight coupling between the scenario construction and DS methods to determine feasible (quantitative or qualitative) decision options under the assumption of underlying scenarios that are subsequently used for the construction of advanced scenarios. In principle, our scenario construction approach is suitable for both fields of application in the domain of decision-making: ad-hoc and proactive DS.

Proactive DS: The approach can be used for the proactive identification of decision recommendations to be well prepared for disasters or to be able to make decisions with long-term effects. In this case, the scenario construction is not based on information already available but on prognostic assumptions concerning possible future developments of the decision environment which are gathered in a collaborative process (i.e. by DMs, stakeholders, experts). In particular, time is not the critical factor for proactive DS. The approach can be conducted iteratively by continuing processing the set of advanced scenarios. Then, additional decision options are determined for the advanced scenarios and new dynamics and developments are investigated when applying these decision options in the decision environment (see Figure 1; dotted line on the right). Proactive decision recommendations are provided for the DMs and can be implemented when an anticipated risk actually occurs and ad-hoc DS measures are required.

Ad-hoc DS: Particularly in the early phases of a disaster, information is often sparse, leading to drop-wise occurrence of new information and the challenge to process this information (if available). To ensure that scenarios are always based on the currently available information, the approach facilitates the iterative update of scenarios in almost real-time when new information arise (see Figure 1, dotted line on the left). Assuming *n* information updates within the decision timeframe, our approach - the two-stage scenario construction - is conducted *n* times. If no information update is available, iterations - as in the case of proactive DS - enlarge the set of decision options and advanced scenarios (see Figure 1, dotted line on the right).The qualitative part of scenario construction can be neglected optionally in ad-hoc DS as time is sparse and the identification of impact factors and their interdependencies do not necessarily require qualitative scenarios. Instead, proactively generated decision recommendations may be an adequate basis to start the construction process.

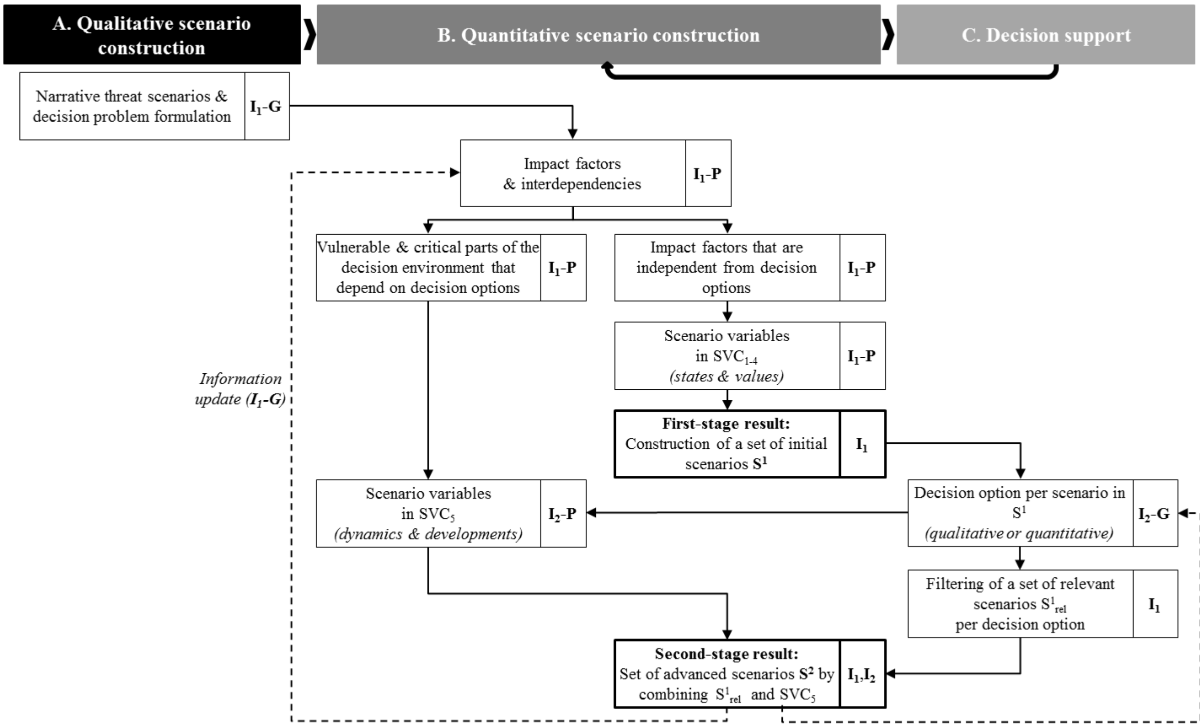

Figure 1: The iterative two-stage evolution of scenarios

Characteristic of our approach are two acquired *information flows* I_1 and I_2 which are needed at different stages of the scenario construction process. I_1 facilitates the construction of initial scenarios and includes collaboratively anticipated (in the case of proactive DS) and available (in the case of ad-hoc DS) information, i.e. specifications of the hazardous event, or the decision environment. I_2 is the explicte result out of the DS-step. It represents the determined decision options for the initial scenarios. In this manner, advanced scenarios can be generated that have not been anticipated so far by disturbing some vulnerable or critical parts which directly depend on these decision options. To highlight I_1 and I_2 within the process and for comprehensibility reasons Figure 1 shows in each step which information flow is addressed and what the current task is (*G*: gathering; *P*: processing).

Qualitative scenario construction

We use narrative scenarios as a first step to analytically forecast future developments within the decision environment. They structure the context of the decision problem to increase the situational awareness of the DMs by determining the questions to be addressed and by this way the kind of scenarios that are needed.

Narrative scenarios are suggested e.g. by R. J. Lempert et al. (2006) who focus on narrative scenarios in combination with robust strategies. The defined scenarios are basically short stories that specify future situations of the underlying scope (in our case a civil security decision problem). Main required characteristics of narrative scenarios are correctness, detailing and realism. A collaborative process is typically needed to create scenarios, implying, however, that they contain perspectives, visions and ideas of all involved DMs. This group is often heterogeneous, consisting of DMs, stakeholders, researchers and experts with multiple goals, preferences and values. Thus, narrative scenarios are debatable as they are never complete in the sense of picturing all perspectives. The structure of a narrative scenario is standardized. The first part introduces the topic and defines the general framework and assumptions. The second part contains the detailed narrative explanation of the future situation. Additionally, impact factors and their interdependencies that may be responsible for the change from the current status to the future state are discussed.

Coupled process of quantitative scenario construction and decision support

Impact factors (qualitative or quantitative) and their interdependencies are derived from qualitative scenarios. Causal maps are a helpful tool to transform narrative scenarios into a structured framework. The identification of impact factors can additionally be supported by measures presented in the previous sections such as the Delphi method that uses expert judgments to identify these impact factors. A scenario variable framework is developed to structure the impact factors as scenario variables (SVs). We distinguish between different scenario variable classes ($SVCs$) including SVs that are independent or dependent from decision options. The SVs in the first group are specified by varying states and values. The SVs in the second group are needed for the second stage of our approach to - after determining decision options - consider dynamics and developments in the decision environment. In this latter case, SVs specify vulnerable or critical parts of the decision environment under the assumption that a certain decision option is applied to the problem at hand. SVs are classified into five scenario variable classes *(*SVC_{1-5}*)*; SVC_{1-4} specify SVs that are independent, SVC_5 includes SVs that represent the vulnerable and critical parts. The characteristics of SVC_{1-4} are summarized in Table 1.

Table 1: Scenario Variable Classes SVC_{1-5}

SVC	Information	Characteristics
SVC_1	deterministic	- SVC_1 contains N_1 SVs which include available and known information - Constant values: value$(SV_i \in SVC_1, i = 1, \dots, N_1)$ = const. in all scenarios - Example: Earthquake epicentre
SVC_2	varying & known preferences	- SVC_2 contains N_2 SVs which include information about DM's preferences - Varying values: values$(SV_i \in SVC_2, i = 1, \dots, N_2) = v_1, \dots, v_m$ - Example: Selected sourcing strategy for logistical services
SVC_3	uncertain (epistemic)	- SVC_3 contains N_3 SVs which include non-available information - Epistemic uncertainties as there is no or less knowledge about possible values of the uncertain parameters - Value ranges for the SVs need to be assumed, i.e. based on historical data, literature reviews or expert opinions - Multiple values: values$(SV_i \in SVC_3, i = 1, \dots, N_3) = v_1, \dots, v_n$ - Example: Behaviour of the socio-economic system due to a disaster
SVC_4	uncertain (aleatoric)	- SVC_4 contains N_4 SVs which include non-available information - Aleatoric uncertainties as the reason for incomplete information is not a lack of knowledge but influences by coincidence - Value ranges for the SVs need to be assumed by statistical distributions based on available or anticipated information - Multiple values: values$(SV_i \in SVC_4, i = 1, \dots, N_4) = v_1, \dots, v_p$ - Example: Temperature mean deviations
SVC_5	vulnerable & critical parts of the decision environment (by decision options)	- SVC_5 contains N_5 SVs that depend on a decision option ($SV_{5,1}$) - SVs aim at disturbing the most vulnerable parts for $SV_{5,1}$ - Multiple or constant values: values$(SV_{5,i} \in SVC_5, i = 2, \dots, N_4) = v_1, \dots, v_z$|const. - Example: Disturbances of the transportation network

The first stage of the scenario construction approach processes the SVs in SVC_{1-4} to construct a set of initial scenarios S^1. Available or anticipated information is processed as a basis for the initial specification of states and values for the SVs, i.e. information about the decision environment, goals and preferences of the DMs or value ranges for uncertain impact factors if available. Based on this information, the SVs are classified into SVC_{1-4} to describe their states. A set of initial scenarios S^1 is finally constructed by aggregating the values for the SVs in a combinatory manner. The second stage of the scenario construction approach aims at considering potential consequences of decision options when vulnerable or critical parts of the decision environment fail. In this way, uncertainties are revealed that have not been obvious so far. Starting point is the determination of a decision option for each scenario of S^1 in the DS part. In the case of quantitative decision options, we suggest using an optimization model to compute the best decision option for each scenario. Alternatively, qualitative decision options can be determined. Note that the exact process of generating decision options is not the scope of this paper but the coupling between these determined decision options and scenario construction. Several decision options may equally qualify as they have been identified as the best decision option for various scenarios. To reduce complexity (a large number of SVs or values for SVs implies a large number of scenarios in S^1), it is important to filter relevant and representative scenarios that are further processed. For more information about filtering techniques to select most relevant scenarios, we refer to the previous work in Comes et al. (2013). The filtered scenarios out of S^1, S^1_{rel}, are needed for the construction of advanced scenarios S^2. Therefore, scenarios in S^1_{rel} - each of them representing values for all SVs in SVC_{1-4} - are aggregated with the SVs in SVC_5. The first SV in SVC_5, i.e. $SV_{5,1}$, is automatically set to the considered decision option. Remaining SVs depend on $SV_{5,1}$ and aim at disturbing vulnerable or critical parts of the new decision environment when $SV_{5,1}$ is applied. The values for the remaining SVs in SVC_5 can be constant or varying (see Table 1).

A decision option is robust, if it performs sufficiently well in uncertain and non-anticipated future developments (Wallenius et al. 2008). Our approach facilitates to test the robustness of the generated decision options in the uncertain future developments $S^1 = SVC_1 \times SVC_2 \times SVC_3 \times SVC_4$. Additionally, the flexibility of a specific decision option is verified in terms of its response to failures of vulnerable or critical parts in $S^2 = SVC_1 \times SVC_2 \times SVC_3 \times SVC_4 \times SVC_5$. Future developments in S^2 have been non-anticipatable so far as they directly depend on the decision option. Note that $|values(SV)|$ and $N_{i,i=1,\dots,5}$ are assumed to be constant for both scenario construction stages. They can, however, differ from iteration to iteration.

Iterative enlargement to a multi-stage evolution of scenarios by updating SVs over time

When conducting our two-stage scenario construction approach iteratively, the approach is enlarged to a multi-stage evolution of scenarios. Referring to the field of application - proactive or ad-hoc DS - two iteration forms are distinguished (see Figure 1, dotted lines). In the case of proactive DS, the two-stage manner of the approach is evolved to a multi-stage scenario construction approach by determining new decision options for the advanced scenarios and considering again the consequences of these decision options. In this way, an enlarged number of feasible decision options are processed into scenarios. This leads to widespread insights into their consequences, weaknesses and vulnerabilities and thus to an increased understanding of the decision environment. Time is not the critical factor for proactive DS. By contrast, time is sparse in ad-hoc DS. Here, SVs and their values need to be updated over time when new information arise. As long as no information update is available, scenarios can be advanced as in the case of proactive DS. Hence, iteration loops for proactive and ad-hoc DS differ: For proactive DS, iterations imply the further processing of the available assumptions (see Figure 1, right iteration loop); for ad-hoc DS, iterations may refer to updated information or the further processing of this information (see Figure 1, left and right iteration loops). Proactive and ad-hoc DS are connected as the proactive results may be the basis for the ad-hoc DS. Although it is not possible to anticipate all scenarios and feasible decision options in advance, proactive DS increases the knowledge about how to work with the approach. Thus, the quality of the finally ad-hoc generated decision recommendation may increase as the scenario construction is then based on proactive results and/or knowledge.

Particularly in ad-hoc DS, the coherent structure of the $SVCs$ becomes obvious. We believe that this SV framework copes with the highest transparency requirements. When information updates appear drop-wise, basically two developments are possible: first, new SVs come up (or rather impact factors) that have not been considered so far and second, new information influences the status of the SVs. In fact, values for the SVs in SVC_2, SVC_3 and SVC_5 can become deterministic over time, leading to a changed status of the SVs. SVC_3, for instance, includes SVs that contain epistemic uncertainties. When information arises over time filling exactly the lack of knowledge for a $SV_i \in SVC_3$, the value for SV_i can be specified with certainty and thus SV_i is shifted to SVC_1. In difference, it is indeed possible to update the values for SVs in SVC_4 (i.e. new information for temperature means) but they cannot become deterministic due to natural deviations that are not susceptible. Of course, at least the subjective variance of the uncertain values for a SV in SVC_4 could decrease due to - for example - increased experiences of the DMs, leading to a convergence of the aleatoric uncertainty towards a deterministic value. The complete acquisition of the variance (and thus the aleatoric uncertainty) is, however, just a theoretical possibility. By defining five $SVCs$, the DMs can transparently identify where the uncertainties arise from and which SVs are known with certainty. Here, the importance to distinguish between epistemic and aleatoric uncertainties becomes obvious. Whereas epistemic uncertainties may become deterministic over time, aleatoric uncertainties include uncertainties during the whole scenario construction process. Note that further shifts of SVs between the $SVCs$ are basically imaginable such as deterministic information becoming uncertain over time but are, for simplifying assumptions, not respected in this paper.

EXAMPLES: APPLICATION POSSIBILITIES FOR PROTECTING FSCS AND PRT SYSTEMS

Protecting FSCs

In various expert interviews with German food supply companies, the following risks for food shortages in Germany were most often mentioned: (1) heat waves, (2) blackouts of IT-systems and (3) staff absence. Various possible threat scenarios exist for each category that may cause food shortages due to, inter alia, disruption of transport and production chains or destruction of inventory. To illustrate exemplarily our scenario construction approach, we present the development of a heat wave threat scenario. Starting point is the narrative description: High outdoor temperature leads to an electricity blackout and thus to a malfunction of the cooling system of a cold storage food warehouse. The company possesses an arborescence distribution network in which one warehouse serves multiple retailers whereas each retailer is supplied by just one warehouse. Furthermore, all warehouses are of the same type. To observe the consequences of this threat scenario, the following decision problem is considered. The company aims at ensuring full service level to satisfy all retailers' demands. DMs decide to temporarily cancel the single-source strategy (that each retailer is supplied by exactly one warehouse) and to establish a new distribution network between warehouses and retailers.

To explore various possible specifications of the threat scenario for the identification of a robust strategy that hedges best against all scenario specifications, the coupled process of quantitative scenario construction and DS is started. We define 13 SVs for SVC_{1-4} including six SVs that are heat wave specific. In the case of road infrastructure, different asphalt qualities of roads are considered as they differ in their critical temperatures for roads damages ($SV_{1,6}$). The planning horizon determines the time frame DMs assume to be faced by the heat wave ($SV_{2,2}$). Transportation time using the roads in the transportation network ($SV_{3,1}$) depends on road capacities that are influenced e.g. by road sizes and traffic ($SV_{3,2}$). The demand for some products may change as demands of the population vary during the heat wave ($SV_{3,3}$). Additionally, the exact specification of the heat wave is uncertain and temperatures may deviate from forecasts ($SV_{4,1}$). Based on the defined values for the SVs in SVC_{1-4} (see Table 2, bride grey section), a set of initial scenarios S^1 is constructed.

Table 2: Example 1 - SVs for FSC protection

SVC	SV	Characteristics
SVC_1	$SV_{1,1}$	Warehouses
	$SV_{1,2}$	retailers and allocation retailers-warehouses
	$SV_{1,3}$	closed warehouse
	$SV_{1,4}$	occupied capacities in warehouses
	$SV_{1,5}$	transport network between warehouses and retailers
	$SV_{1,6}$	temperature-critical routes (i.e. due to the asphalt quality)
SVC_2	$SV_{2,1}$	transportation mode
	$SV_{2,2}$	planning horizon
	$SV_{2,3}$	sourcing strategy
SVC_3	$SV_{3,1}$	route durations in the transport network
	$SV_{3,2}$	route capacities
	$SV_{3,3}$	demand of retailers
SVC_4	$SV_{4,1}$	deviations of forecasted temperature means
SVC_5	$SV_{5,1}$	decision option
	$SV_{5,2}$	malfunction of routes depending on $SV_{1,6}$ and $SV_{4,1}$
	$SV_{5,3}$	malfunction of highest capacitated route

As remarked by several reviewers, it would be valueable for this paper to illustrate some results we have obtained from our scenario construction approach. Due to space restrictions, an extensive illustration is, however, not possible within this paper. At least, we highlight the amount of initial scenarios S^1 which are constructed in this example. Scenarios in S^1 are consistent combinations of SVs in SVC_{1-4}. The values of SVs in SVC_1 and in SVC_2 are constant ($SV_{2,1}$: road; $SV_{2,2}$: 24 hours; $SV_{2,3}$: multiple-sourcing). As $SV_{4,1}$ does not become relevant before the second stage to construct advanced scenarios S^2 (as $SV_{4,1}$ depends on $SV_{5,2}$), the specifications of initial scenarios is the aggregated combination of values of SVs in SVC_3. In total, 4 (number of

$SV_{3,1}$ value patterns) * 4 ($SV_{3,2}$ value patterns) * 5 ($SV_{3,3}$ value patterns) = 80 initial scenarios are constructed. The value patterns have been determined in a collaborative process by the partners in the SEAK-consortium.

The decision problem corresponds to a capacitated facility location problem (CFLP) and is solved for each scenario in S^1. The decision variable x_{ij}^s is the CFLP-result for a scenario s. It specifies the percentage of the demand of retailer i which is satisfied by warehouse j. To get the total amount of food that is supplied by j to i, x_{ij}^s is multiplied by the overall demand of retailer i. The determined decision options are subsequently tested for all scenarios in S^1 to measure their robustness. All scenarios in S^1 contain a functioning transportation network (road infrastructure, no roads damages). To verify if a decision option performs well in the case that vulnerable parts (roads) of the decision options fail, we construct an advanced set of scenarios S^2 following the second stage of our approach. We aim at testing the flexibility of the decision options ($SV_{5,1}$) responding to critical disruptions for (i) the total malfunction of routes depending on $SV_{1,6}$ and $SV_{4,1}$ and (ii) depending on the highest capacitated road for each decision option specifying the most vulnerable part of the supply network (SN). The former is defined by $SV_{5,2}$ and the latter by $SV_{5,3}$ (see Table 2, dark grey section). Although we expect that most decision options perform insufficiently for the scenarios in S^2, the results are useful to consider which decision option facilitates the maintenance of the SN although vulnerable parts fail. The iterative process can be started by using the CFLP again to determine more promising decision options for the scenarios in S^2.

Protecting PRT systems

To identify terroristic threats against PRT systems, scenario-based risk analysis is helpful. A possibility to start the scenario construction is the identification of so-called Vignettes. A Vignette describes unambiguously the combination of three (epistemic) SVs: attackers' motivation ($SV_{3,1}$), weapon ($SV_{3,2}$) and target ($SV_{3,3}$). When supplemented with a detailed description of the scenario environment and course of the attack, any Vignette becomes a scenario. However, because the number of possible terrorist threat scenarios is infinite, the identified set of scenarios S^1 is only a small representation of plausible scenarios, based on expert surveys and the evaluation of historic terrorist events. In RIKOV, for instance, the project consortium solely focuses on applying the approach to the defenders' (public railway system operator) point of view. For the sake of completeness we have to mention that our approach would also work when focusing on the attackers' (terrorist) point of view. In addition to the three epistemic SVs as mentioned above ($SV_{3,1}, SV_{3,2}$ and $SV_{3,3}$), we identified eight more different SVs (see Table 3, bride grey variables). Epistemic and aleatoric SVs exclusively depict the attackers' behavior and associated consequences of the attack. These variables are of generic nature and thus are applicable for all scenarios (Vignettes). An expert panel identified 14 specifications for $SV_{3,1}$ (e.g. explosives, firearms, WMD), 17 for $SV_{3,2}$ (e.g. trains, train stations, SCADA systems) and 4 for $SV_{3,3}$ (individual or group, with and without suicidal intention), whereas the latter can furthermore be differentiated according to their motives and capabilities. In total, 94 realistic combinations of $SV_{3,1}$, $SV_{3,2}$ and $SV_{3,3}$ have been identified (some combinations are not plausible). These combinations, when complemented with a description of the course of the attack ($SV_{3,4}$), form an initial scenario which then can be specified when adding values to all the other SVs.

Table 3: Example 2 - SVs for PRT system protection

SVC	SV	Characteristics
SVC_1	$SV_{1,1}$	PRT system (including relevant system elements)
	$SV_{1,2}$	transportation capacities
	$SV_{1,3}$	system vulnerabilities
	$SV_{1,4}$	passengers' behaviour (average passenger numbers, rush hours etc.)
SVC_2	$SV_{2,1}$	safety measures (safety concept)
SVC_3	$SV_{3,1}$	attackers' motivation and capacity
	$SV_{3,2}$	attackers' weapon
	$SV_{3,3}$	attackers' target
	$SV_{3,4}$	course of the attack
SVC_4	$SV_{4,1}$	attackers' decisiveness (depending on opportunities to attack)
	$SV_{4,2}$	effectiveness and consequences of the attack
SVC_5	$SV_{5,1}$	decision option
	$SV_{5,2}$	attackers' reaction (depending on decision option)

To carry out a scenario-based risk analysis, the variables and the resulting scenarios S^1 are used for a classic scenario-based risk analysis where risk is defined as a function of threat, system vulnerabilities and consequences of the attack. This analysis is the basis for an associated risk management process, to create adequate safety and security measures for each investigated threat scenario. The set S^1 thereby allows validation of the existing or proposed safety and security concept (decision option). At the second stage of our scenario construction process where the advanced scenarios S^2 are constructed, the only additional considered element is the attackers' reaction to our identified decision option which can be understood as the most vulnerable or critical aspect (see Table 3, dark grey variables). Before iteratively starting our approach again, we recommend an intermediate step. Since classic risk analysis approaches cannot sufficiently handle the problems associated with intelligent adversaries (e.g. processing of new available information, adaption of strategies), the attackers' reactions to our identified decision option(s) need to be taken into account as well as the attackers' behavior in decision situations. If not, the results of the scenario-based risk analysis surely will lead to a false allocation of limited resources or even might increase risk rather than decrease it (Cox 2008; Cox 2009). One possibility to do so is applying game theory to analyse risks arising from intelligent adversaries with classic defender-offender-games. Information gained in this intermediate step then enters the next iteration step.

DISCUSSION AND CONCLUSION

Our approach is versatile as it can handle natural (or random) risks as well as risks that arise from intelligent adversaries. With the proposed approach we are capable to provide ad-hoc (i.e. crisis management) and proactive (i.e. strategic planning) DS. Protecting CIs basically implies that the provided recommendations are developed in a proactive manner to be well-prepared for the case of a disaster. The security of food supply chains, as it is the case in SEAK, refers, however, preliminary to ad-hoc decision situations since its focus is on crisis management (as facility location problems usually require strategic and thus proactive DS, a clear distinction between proactive and ad-hoc DS is necessary). In contrast, protecting PRT systems, as it is the case in RIKOV, deals solely with proactive DS because the focus here is on safety and security concepts which aim at preventing any kind of disaster. The emphasis of our scenario construction approach is on the identification of critical or vulnerable elements when applying decision options in complex decision environments under great uncertainty. As the approach is generic by nature it is applicable to a wide range of decision problems (see above), and it can deal with both internally and externally induced risks. By structuring the process of scenario construction, the DMs get a clear picture of relevant parameters of the decision situation to enable a transparent decision-making process. Our iterative approach supports robust and flexible decision-making because it enables the DMs to improve their decision options step-wise when new information gets available or to refine previous decision options step-wise when no new information is available. By systematically integrating new information and processing them, scenarios sample the space of decision options in a sufficient manner. The evolutionary element of the approach, the dynamic and endogenous increase of knowledge about the decision options' background, can be coupled in this case with the capturing and processing of new information in almost real-time (if new information is available). The combination of exogenous and endogenous information processing is the main and novel feature of our contribution.

Although we are convinced of the generic applicability of our approach, we want to comment its limitations and spaces for improvement. Particularly the last mentioned aspect, the processing of information in almost real-time (ad-hoc DS), is crucial. An information system (IS) is needed that gathers information and prepares it in a way that enables to use it for scenario construction. The adequate design, implementation and, execution of such an IS should be the scope of future research. Moreover, the quality of the DS as a whole depends to a high extent on the constructed scenarios. In our approach, we suggest starting the process with expert talks to identify impact factors as the basis for the design of SVs. Acquiring valid impact factors thus depends on the work of these experts and, in contrast, on the collaborative approaches used to support these experts (i.e. Delphi method). Only if such approaches are accurately chosen and prepared, a sufficient basis for starting the automated scenario advancement is established. Particularly when applying the approach in an ad-hoc decision situation, the selection of collaborative approaches and the provision of guidelines how to use them in our scenario construction approach are indispensable. This work has to be done additionally because decisions are required quickly (i.e. in disaster response) and a certain time is already "wasted" just to set up the expert panel. Otherwise, the scenario construction process will likely start flawy, threatening the total benefit of the approach.

One can say that if the threat is of physical nature and has a natural (or aleatory) origin, our approach can be applied without any adaptations and extensions. If the threat situation depends on the reactions and the behavior of the decisions makers or intelligent adversaries, an intermediate step is required. How this intermediate step should look like has to be the topic of further research as well as how the DMs' behavior under stress influence finding robust decision options. Moreover, future research needs to focus on the quantitative evaluation of results that are generated out of our approach. Also appropriate methods to review accuracy of the defined SVs need to be investigated, just as methods to generate robust decision options (i.e. stability and quality indicators of results across scenarios and methods of multi-attribute decision making to identify the best decision option) need to be tested.

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