Modeling of countermeasures for large-scale disasters using High-level Petri Nets

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ABSTRACT

In order to support decision-making in large-scale disasters, IT-based decision support systems provide appropriate countermeasures to respond to the event. For the implementation of measures, logical and temporal dependencies have to be considered. Furthermore, factors influencing the choice of measures should be taken into account. This paper presents a generic approach to modeling sequences of countermeasures using High-level Petri Nets including information about the influencing factors and endangered objects. Moreover, an approach to combining several nets is proposed, which establish new sequences for recommendation. The research is part of the development of a generic decision support system for large-scale disasters. Consequently, the focus is on modeling in a generic manner and on automatic processing.

Keywords

Disaster management, High-level Petri Nets, decision support system

INTRODUCTION

In the event of a large-scale disaster, IT-based decision support systems (DSS) provide potential solutions to respond to the disaster and assist in the decision-making process. Case-based reasoning (CBR) is a possible methodology which can be used in this context. A crucial part in the CBR cycle is the reuse step which is the subject of this paper. In the DSS to be developed a case consists of an event description using attribute-value pairs and a sequence of countermeasures which represents the solution. The solution of the most similar case does not have to be the best one (the definition of "the best solution" needs to be discussed, which is beyond the scope of this paper). Moreover, information about less successful solutions is also valuable for decision-making. Therefore, to make appropriate recommendations the k most similar cases are reused (k could be a fixed number or the number of cases whose similarities exceed a certain threshold). The question that arises is how to model a sequence of countermeasures providing reasonable information content to make past decisions comprehensible. Moreover, several retrieved sequences should be processed automatically.

The objective of this paper is to illustrate an approach to modeling sequences of countermeasures using High-level Petri Nets (HLPNs). A generic approach is required which matches the generic framework of the DSS to be developed. Furthermore, modeling also is to cover information necessary to make the sequence of countermeasures comprehensible. Petri Nets (PNs) are considered as an effective tool meeting these demands. They can be used for modeling and analysis, simulation and good graphical representation. Moreover, they allow for the modeling of sequential and parallel countermeasures. Modeling a sequence of countermeasures including sub-events and endangered objects leads to many states and increasing complexity. HLPNs allow for a clear representation of complex issues. As will be shown later, the generic modeling with automatic processing can be applied to different kinds of disasters. PNs are applied successfully in various fields. Especially in the area of emergency and disaster management and accident modeling, various applications of PNs exist as can been seen in the literature review.

The paper is organized as follows. First, existing approaches to modeling disaster and emergency management activities will be presented. Second, the modeling requirements will be discussed. Third, the proposed model for the countermeasures will be introduced, followed by a framework for the reuse step, including a small example. The paper will be concluded with a discussion of future work.

LITERATURE REVIEW

In order to analyze existing approaches, papers in the area of disaster recovery planning/strategies, disaster and accident rescue (processes), disaster/emergency response (activities), post-disaster rebuilding, disaster/emergency management, and emergency plans were studied with regard to modeling and the possibility of automatic processing. Franke, Charoy and Ulmer (2012) present an activity management system for the temporal coordination of disaster response activities. Optimization and project management approaches in the context of disaster plans (Bryson, Millar, Joseph and Mobolurin, 2002; Kim and Choi, 2012) and rebuilding projects (Yan, Jinsong, Xiaofeng and Ye, 2009) are interesting for performance analysis.

A broad and important field is process modeling, such as process-oriented modeling of emergency management measures (Rüppel and Wagenknecht, 2007) with possibilities of process adaptation (La Rosa and Mendling, 2008). Sell and Braun (2009) developed a workflow management system to support the modeling, execution, and management of emergency plans. PNs are widely used for emergency management. Ju, Wang and Che (2007) use Generalized Stochastic PNs to model a traffic accident rescue process with the aim of identifying weaknesses and optimizing rescue teams. Stochastic PNs can be used to analyze and simulate a coal mine emergency process (Ma, Li and Chen, 2011) and to model an emergency response decision-making process (Shan, Wang and Li, 2012) for performance analysis. Wei-Dong and Zhe (2011) use Colored PNs to model an emergency plan business process. Fahland and Woith (2009) model adaptive disaster response processes, in which the behavior is synthesized by scenarios at run-time. They argue that processes in this context are subject to complex dynamics and tasks and sub-processes are event-driven. PNs are also used for accident modeling. The difficulty is to transfer a text into a formal model (Hill and Wright, 1997). Vernez, Buchs and Pierrehumbert (2003) emphasize the huge potential of PNs in the field of safety and present translations of safety concepts into PN structures.

The PN approach seems to be very promising for modeling and later performance analysis. All approaches listed above focus on different aspects of disaster/emergency management. However, they do not address all requirements relevant to the problem discussed, such as the applicability to different kinds of disasters and the integration of aspects leading to the decisions. In order to comply with the requirements, the different and very interesting approaches and views of the problem are utilized and improved.

MODELING REQUIREMENTS

The countermeasures to be suggested by the DSS are to comprise disaster response measures and long-term strategic decisions. Based on requirements extracted from flood reports (Arbeitsgruppe Hochwasser (Sachsen-Anhalt), 2003; Unabhängige Kommision der Sächsischen Staatsregierung, 2002) and the analysis of related work, the following qualitative aspects were found to be important. The order of the countermeasures implemented has to be considered. As the focus is on learning from the past, crucial factors influencing the decisions have to be taken into account. Performance analysis has to be included. A graphical representation supports the understanding of coherence and should be taken into consideration. Furthermore, easy extension of the model should be ensured to include additional information about the event. The vocabulary for event and measure description should be generic in order to facilitate automatic processing. The fire departments service regulations (Feuerwehr-Dienstvorschriften FwDV) governing the activities of the German fire departments should also be taken into account. FwDV100 in particular outlines situation assessment based on information about the location, time, weather, damage, damaged object, and extent of damage which determines the planning process and the resulting measures.

MODELING SEQUENCES OF COUNTERMEASURES

PNs can be used to describe and analyze system behavior (Baumgarten, 1990; Peterson, 1981). There are different types of nets which can be divided into Low- and High-level PNs. In Low-level nets tokens are indistinguishable. In HLPNs (Jensen and Rozenberg, 1991) tokens have individual characteristics and therefore can be distinguished. Each place, transition, and arc is defined with respect to different token types. HLPNs allow for a more compact description than Low-level nets. For practical applications, they are preferred to Low-level nets (Oberweis and Sander, 1992). A general definition of HLPNs can be found in ISO/IEC 15909.

Model

The following assumptions are made: There are two active components, the countermeasures and the events/ causing factors. Countermeasures are decided upon and implemented because of an event (or an unfavorable state) and the resulting endangered objects. Each event causes endangerment or creates endangered objects. Countermeasures mitigate the endangerment and process endangered objects. They do not create endangerment.

The formal model is a tuple $(P, T, D, Type, Pre, Post, M_0)$ where

- P is a finite set of places.
- $T = T_m \cup T_e$ is a finite set of transitions where T_m denotes the set of countermeasures and T_e denotes
- the set of (sub-)events. It holds that $P \cap T = \varnothing$. Moreover, there are finite sets of labels for measures Σ_m and events Σ_e and labeling functions $L_k : T_k \to \Sigma_k, k = m, e$ which assign labels to the transitions
- from a predefined value range.
- D is a nonempty finite set of endangered objects. Moreover, a token without characteristics
- representing the dynamics is included. Let $\wp(D)$ be the power set of D .
- $Type : T \to \wp(D)$ is a function which assigns endangered objects to transitions.
- $Pre, Post : TRANS \to \mu PLACE$ are pre- and post-mappings with
- $TRANS = \{(t, m) \mid t \in T, m \in Type(t)\}$
- $PLACE = \{(p, g) \mid p \in P, g \in D\}$
- $\mu PLACE$ is the set of multisets over the set $PLACE$.
- $M_0 \in \mu PLACE$ is the initial marking of the net.

The basic structure of an HLPN as defined in ISO/IEC 15909 is adapted according to the assumptions above and the labeling of transitions (Murata, 1989) is integrated. The net has two types of transitions, events and countermeasures, which can be distinguished by their handling of tokens. Tokens contain information about endangerment and the endangered objects. Extension to cover further information is possible. If a transition representing an event has occurred, endangered objects are inserted into the output place(s). If a measure completely counteracts an endangerment, after occurrence, the output place(s) of the corresponding transition is/are marked by tokens without characteristics. An example is the successful evacuation of the endangered object 'residential area'. Transitions allow for specific types of tokens. Assume there is a release of a hazardous substance. The transition with the label 'closing the windows' represents a countermeasure and allows for 'residential area' as a token. Animals as other endangered object, will be processed by another transition.

FRAMEWORK FOR THE REUSE STEP OF THE CBR CYCLE

In the reuse step the sequences of the *k* most similar historic cases are combined in order to illustrate possible sequences of events and measures. The idea is to put shared patterns on each other by means of fusing transitions with the same label without losing the firing sequences of each involved PN. The involved places in the images of the *Pre* and *Post* mappings of the fused transitions have to be fused, too. The entire net is generated by successively combining the *k* nets.

Figure 1 illustrates the ideas for flood scenarios. For reasons of clarity, the example is deliberately kept simple. It is not meant to over-simplify disaster response or decision-making. The oval circles depict the places and the rectangles depict the transitions. Those with dashed lines refer to events, whereas the grey rectangles refer to the measures. The tokens represent the endangered objects 'city' and 'chemical park' without any further information. A token without characteristics is added, which is illustrated by a black dot. Transitions will be referred to by their labels. The arcs are annotated according to transition behavior. Annotations on output arcs of an event transition illustrate the endangered objects generated by an event. Annotations on input arcs of a countermeasure transition show which endangered objects are handled by a countermeasure. Annotations on output arcs of countermeasure transitions depict the extent to which the countermeasure contributes to the mitigation of endangerment. It is assumed that measures completely reduce the endangerment. This is illustrated by a black token on output arcs of countermeasure transitions.

In net N_1, a leaking dike endangers a city and a chemical park which is illustrated by the two tokens on the output arc of event transition 'leaking dike'. The measure 'dike protection' can handle both endangered objects. In the scenario a dike failure occurs. In order to protect the city and the chemical park, an evacuation and unscheduled flooding are necessary. The net $\hat{N}$ illustrates the combination of N_1, N_2 and N_3. The transitions 'dike protection', 'dike failure' and 'flooding' are fused. The previous three firing sequences of N_1, N_2 and N_3 are extended by seven additional sequences. For example, 'overflow of dike', 'dike protection', 'water level rise' and 'protection barrier' would be a new sequence.

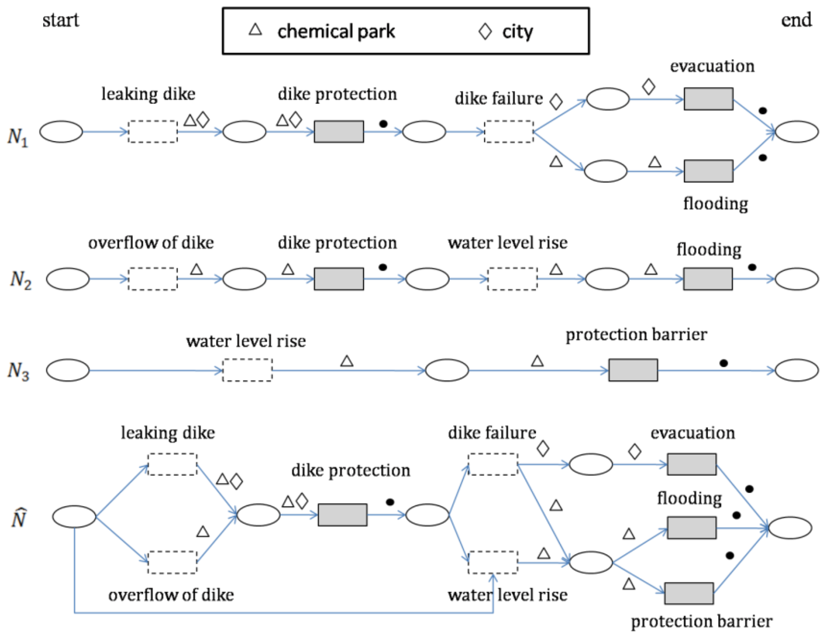

Figure 1. Example of combination of three Petri Nets

Modeling of the sequences is generic, as the approach does not focus on a specific kind of disaster. Moreover, important aspects, such as influencing (sub-) events and endangered objects, which make the choice of measures comprehensible are included. Furthermore, the finite set of labels and the finite set of endangered objects enhance automatic processing. The first step is to combine the retrieved PNs in order to obtain all possible firing sequences, including the previous sequences of the involved nets. The advantage is that new sequences are gained for recommendation. Moreover, possible event developments and endangered objects can be detected. As the approach is generic and automatic processing is guaranteed, the framework can be integrated in the decision support system to be developed.

DISCUSSION AND FUTURE WORK

This paper presents a generic approach to modeling sequences of countermeasures with the help of HLPNs. Research is part of the development of a generic decision support system for large-scale disasters using CBR. A case consists of a description of an initial situation and a solution, including event developments and/or implemented measures. For case description, general attributes, such as 'time', 'location' or 'endangered objects' and event-specific attributes are used. In the HLPNs there are two kinds of transitions referring to (sub-) events and countermeasures. The value range for the transition labels is predefined. The tokens are provided with information about endangerment or endangered objects generated by event transitions and mitigated by measure transitions. One part of the reuse step is to combine several PNs by fusing transitions with same labels. The objective is to identify possible processes and new sequences of countermeasures without losing the original firing sequences. This was illustrated by a small example.

For future work, the model will be enhanced. The reuse step in particular will have to be formalized and implemented, including an approach to performance analysis of the sequences of countermeasures. Moreover, the resulting sequences will have to be tested for logical errors and a guard function will have to be included. The fact that several measures have to be implemented to mitigate an endangerment requires further analysis. An idea is to add the percentage of mitigated endangerment to the token characteristics. Time factors and uncertainties should be integrated, too. As regards the time, duration of the implementation of countermeasures might be possible. Uncertainties with respect to the events might be considered, which means that certain probabilities might be indicated for event developments.

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