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Modeling method of cascading crisis events based on merging Bayesian Network

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ABSTRACT

This paper presents a Bayesian Network (BN)-based modeling method for cascading crisis events. Crisis events have occurred more frequently in recent years, such as typhoons, rainstorms, and floods, posing a great threat to humans. Addressing these crises requires a more effective method for crisis early-warning and disaster mitigation in crisis management. However, few modeling methods can combine the crisis chain reaction (macro-view) and the elements within the crisis event (micro-view) in a cascading crisis events. Existing classical methods fail to consider the causal relations linking the micro to macro level in crisis events, which affects the forecasting accuracy and effectiveness. Based on systems theory, this paper first abstracts the crisis event as a three-layer structure model consisting of input elements, state elements and output elements from a micro-view. Next, a cascading crisis events Bayesian Network (CCEBN) model is developed by merging the single crisis events Bayesian Networks (SCEBNs). This method efficiently combines the crisis event's micro-view and the macro-view. The proposed BN-based model makes it possible to forecast and analyze the chain reaction path and the potential losses due to a crisis event. Finally, sample application is provided to illustrate the utility of the model. The experimental results indicate that the method can effectively improve the forecasting accuracy.

1. Introduction

A well-performed emergency decision support system (EDSS) plays a crucial role in emergency-warning and disaster mitigation of crisis management. To save lives and prevent additional property damage, several models for EDSS have been developed in the field of crisis management. However, these models did not comprehensively utilize the information of the whole crisis environment, which was restricted to be specific to its own context. Most of the former studies focused only on a single crisis event (such as the artificial neural network-based EDSS [1], nuclear emergencies [2], hurricanes in Florida [3], floods in Italy [4], among others). These methods overlook the interactions among different crisis events, which results in a low forecasting accuracy. When a crisis event occurs, it usually leads to secondary events or derived events. Specifically, there are causal relations among the different crisis events. The occurrence and development of one event always has impact on the other events. This phenomenon can be called chain reaction of crisis events. These corresponding associated crisis events form a cascading crisis event.

It is helpful to improve the effectiveness of crisis management by understanding a crisis event and identifying its cascading event comprehensively as well as accounting for the chain reaction information. Several methods include this principle, but most of these studies take the crisis event as a node with a macro-view, which cannot reveal the evolution mechanism of the cascading crisis events completely. For example, some studies focused on the qualitative analysis of a domain-specific cascading crisis event, such as a geological-hazard chain [5,6], sediment-hazard chain [7], disaster mitigation framework [8], and typhoon-hazard chain [9]. These studies especially focused on researching the interior mechanisms and manifestations of domain-specific cascading crisis events qualitatively but did not provide any modeling methods for the cascading crisis events. Other researchers focused on modeling the chain effects of the cascading events. J. T. Rodriguez et al. [10] proposed an alternative data-base approach to assessing the potential damage that can arise from various combinations of phenomena and locations. However, this method will result in too many rules to model the complexity and uncertainty of the problems. C. Fang et al. [11] proposed a simulation-based risk network model for decision support in project risk management. This method accounted for the phenomena of chain reactions and loops, but it neglected the detailed connections of information among the internal components of a cascading crisis event. J.W. Wang et al. [12] studied the network model of the chain reaction based on complex network theory. They analyzed the topological features of the network from only a macroscopic perspective. However, all these methods could not consider both the crisis chain reaction (macro-view) and the elements within the crisis event (micro-view) in a cascading crisis event.

Therefore, to make effective use of the chain reaction information and to reveal the evolutionary mechanism of the crisis event, it is important to model the cascading events by combining a single crisis event

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from a micro-view with the associated crisis events from a macro-view. This paper proposes a novel Bayesian Network (BN)-based modeling method that can combine the information that comes from the internal crisis events and the chain reaction process. In contrast to the traditional macro analysis methods, this paper focuses on the evolutionary mechanisms of crisis events and combines the microscopic and macroscopic ways of analyzing the chain reaction path and predicting the potential losses of the crisis events. An example of a typhoon–rainstorm–flood disaster chain is taken to demonstrate the validity of the proposed method.

The remainder of this paper is structured as follows. Section 2 discusses why BN is used as the modeling tool. In Section 3, a single crisis event Bayesian Network model (SCEBN) is constructed. Section 4 proposes the cascading crisis events Bayesian Network (CCEBN). And an implementation of the CCEBN-based EDSS is presented in Section 5. Section 6 presents an experimental example to evaluate the model. Finally, in Section 7, we conclude with a summary and a statement concerning possible future research.

2. Why Bayesian network?

The crisis system is an open, complicated and enormous system, which has the characteristics of multi-agents, multi-factors and variability [13]. A well-performed emergency decision support system plays a crucial role in emergency-warning and disaster mitigation of crisis management. Several modeling approaches have been used to develop EDSS for crisis management. Bayesian Network (BN) modeling and hierarchical simulation-based modeling are two major approaches in event modeling [14,15]. Additionally, there are a few researchers who use matrix-based methods to model the relations and dependencies among the risks [6]. In hierarchical simulation-based modeling, the often analytically intractable probability distributions are estimated by generating samples from the distributions by simulation [15], which will take a rather long time. Moreover, the hierarchical simulation-based modeling is especially suitable for cases that have relatively abundant knowledge of complicated interactions among the model variables [16]. For the matrix-based methods, the network model and parameters are all constructed by experts, and the data used in the model is from expert experience. Additionally, the experts should participate in the whole process of the DSS to construct the risk network model and decide on the risk response plans [6]. However, it is often difficult to find enough experts in real-life crisis management, especially in an emergency.

The evolutionary mechanism of crisis events as well as the relationships among them is complex and indicates the traits of uncertainty [17]. When one crisis event triggers a series of secondary events and derivative events in a cascading crisis event, the external environment factors and causal relationships among the crisis events all have uncertainty. A BN model can represent explicitly the system's complexity in terms of variables and their causal-effect relations, in a descriptive way [18]. Moreover, the probabilistic representation of the interactions among the variables allows for the estimation of the crisis and uncertainties better than models that account for only expected values. The technique can combine the experts' knowledge into the model, and because BNs are solved analytically, it can provide fast responses to queries once the model is compiled [16]. Thus, the BN technique is ideal to support crisis system modeling.

In a decision-making context, the BN can be used for modeling the crisis system when it is used to describe and abstract the system that is being studied. When the decision and utility nodes are abstracted in the network, the BN model can conduct an Influence Diagram. Then, the BN can be employed as a decision support system that aids in decision making. Furthermore, the BN can also be used as a visualization tool to summarize simply the outcomes of more complex models [19].

3. Single crisis event Bayesian Network model

3.1. Three-layer structure model of single crisis event

During the occurrence and evolutionary process of the crisis events, there are constant exchanges of matter, energy and information between crisis events and the external environment [17]. Based on systems theory [20,21], we abstract the elements that are related to the crisis events into three groups, which are input elements, state elements and output elements. From this viewpoint, the crisis event can be abstracted as a generic three-layer structure model that is expressed as $CE = \langle I, S, O \rangle$, where $I = \{i_u | 1 \le u \le l\}$ is the input element set of CE, $S = \{s_v | 1 \le v \le m\}$ is the state element set, and $O = \{o_w | 1 \le w \le n\}$ is the output element set of CE. Furthermore, let $s^e \in S$ denote a special state variable that marks whether a crisis event occurs or not, and we call it a trigger state variable. Each crisis event is triggered by several key state variables. Based on these variables, the value of s^e can be calculated. Thus, the crisis event can be judged as to whether it occurred or not according to the value of s^e. Fig. 1 illustrates the three-layer structure model of the crisis event.

(1) *Input element*. The input elements refer to the external factors, which can result in the changes of the crisis event's internal states. The input elements can be divided into the environmental input (EI) and the control input (CI), with $I = EI \cup CI$. The environmental inputs $EI = \{ei_t | 1 \le t \le \alpha\}$ include abnormal substances, energy and information from the external environment, which will affect the crisis event's state and then lead to the crisis event's occurrence and the evolution of the crisis events. The control input $CI = \{ci_t | 1 \le t \le \beta\}$ can be considered to be a set of emergency response activities that are taken by the related organizations to prevent the evolution of crisis events according to the event's states, to reduce the losses.

(2) *State element*. The state elements are used to describe the nature and characteristics of the crisis event system's occurrence and evolutionary process. It include the states of the event (EP), the states of the event life cycle lc, and the states of the hazard-affected body (BP), where the hazard-affected body means a series of entities that can be affected by crisis events, such as population, buildings, and other factors. $EP = \{ep_t | 1 \le t \le \lambda\}$ describes the key characteristics of the event, such as the event level or influence scope. $BP = \{bp_t | 1 \le t \le \gamma\}$ describes the states of the hazard-affected bodies that are influenced by the crisis event. Additionally, lc describes which stage the crisis event is in its

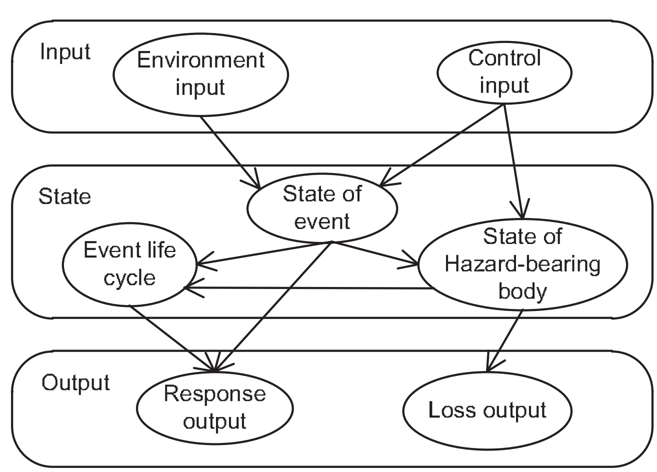

Fig. 1. Three-layer structure model of a crisis event.