Scenarios Conversion Deduction Method of Natural Disaster Based on Dynamic Bayesian Networks

Xiao-han ZHU, Xiang-yang LI, Shi-ying WANG and Zhao-ge LIU
School of Management, Harbin Institute of Technology, Harbin 150001, China
*Corresponding author

Keywords: Natural disaster, Scenario, Conversion deduction method, Dynamic Bayesian network.

Abstract. Based on scenario analysis, this paper makes a definition of natural disaster scenario type and concept from different aspects, describes the mechanization of the development of natural disaster chain scenario and applies Dynamic Bayesian Network. It uses probability assessment to analyze the transformation rules in the development of natural disaster chain scenario, to make up the shortage of the traditional method to capture the dynamic changes of the natural disaster chain, and to provide support for the prediction, decision and response of the natural disasters.

Introduction
In recent years, natural disaster scenarios deduction is changed from qualitative assessment to semi-quantitative or quantitative assessment, the common methods are probability statistics\(^1\), fuzzy mathematics\(^2\), information diffusion theory\(^3\), hierarchical analysis\(^4\), gray system\(^5\), artificial neural network\(^6\), weighted comprehensive evaluation\(^7\) and so on. Because of the uncertainty of the process of natural disaster, researchers always establish the relationship of scenario by Bayesian network\(^8-9\), and estimate the natural disaster deduction paths through prior probability and sequence probability. But natural disaster scenario is dynamic, static Bayesian network applies only to the current moment, and can’t capture the deduction direction of next time. According to the above problem, the paper draws the interdependence of scenario elements by dynamic Bayesian network, and calculates scenario conversion probability to judge scenarios conversion rulers.

Scenarios Expression Style
In the process of scenario conversion, the conditions and variables are changing, and the natural disaster scenarios can be described as a triple by time sequence, that is \(S = < TP, SE, DE >\).

- **TP**—Element type. According to different content, elements can be divided five types, that is timestamp (T), disaster factors (H), hazard-affected bodies (L), environmental (E), effect factors (R) and event chain (N).
- **SE**—Elements. It refers to the name of elements.
- **DE**—Element attributes. It is a variable of describing of properties, status, and relationship.

Natural Disaster Scenarios Conversion Deduction Model
Natural disaster scenarios conversion deduction is a dynamic process from the dimension of time, so the state of the natural disaster (scenarios element) shifts constantly. When the value of element reaches to a critical point, scenarios generate great transformation, and formed a link between two scenarios, that is the transformation between scenarios satisfies a certain probability distribution. Above all, establishing an interdependent of scenarios is needed through probability distribution to capture conversion rules. Circulars denote scenario, the lines with short arrow denote scenario conversion paths and directions, and transformation model is shown in Fig. 1.

![Figure 1. Natural disaster scenarios conversion deduction model.](image-url)
In the figure, \( u \) said scenario conversion parameter vector, \( t_u \) said the time of scenario conversion, \( s_u \) said the attribute parameter of scenario conversion, \( p_u \) said the scenario conversion probability. We have known the describe method of \( s_u \), now we calculate the value of \( p_u \). In recent year, static Bayesian network has strong ability of handing uncertainty problems, can express and fuse multi-source information, and accommodate the incomplete information, so this method is widely used in areas of disaster “Scenario-Manage”. But it can’t solve the timing problems, that is, it doesn’t consider the each moment interaction between scenarios. Above all, in order to describe the state change of natural disaster scenario situation, establishing a dynamic Bayesian network, the specification steps are as follows:

Step 1: Collecting data and extracting features.
Step 2: Establishing Bayesian network.
Step 3: Calculating the prior probability and conditional probability.
Step 4: According to the existing evidence, predicting natural disasters scenario conversion paths in the future.

**Building Bayesian Network**

Natural disaster scenario description is composed of five elements, respectively are disaster factors, hazard-affected bodies, environment, effect factors and event chain, using timestamp can distinguish effectiveness of each element. So, the method can extract the characteristic value of natural disaster based on the type of elements, and establish the Bayesian network diagram in accordance with the time order, as shown in Fig. 2.

![Figure 2. Natural disaster scenarios conversion deduction model.](image)

Bayesian networks can clearly show the causal relationship between scenario elements, and this causal relationship is great uncertainty with changeable transformation direction, there are two main styles. Set \( S = \{s_i\} \) as scenario set, \( RE = \{s_i, s_j\} \) as the relationship between scenarios, and each scenario can take values 0 or 1, 1 represents the scenario happening and 0 adverse. Logical relationship mainly includes: “And” type and “Or” type, description symbol as shown in table 1.

The causality of great uncertainty, transformation direction is uncertain; there are two main types of the way. Set a scene set, for the relationship between scenes, each scene has two values 0 s and 1 s, one representative scenarios, 0 represents the situation did not happen, logical relationship mainly includes: type "and" and "or" type, description symbol as shown in Table 1.

Relationships between scenarios correspond with Bayesian network, and transformation probability is the sequence scenario generating probability under the condition of the happening of prior scenario. Therefore, Bayesian network can show the relationship, the specific transformation rules are shown in Table 2.
Table 1. Scenario relationship symbols.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Symbol A" /></td>
<td>“And” Type: Scenario $s_i$ and scenario $s_j$ happen at the same time, $s$ can happen, that is ${s_i = 1 \text{ and } s_j = 1} \rightarrow u_s = 1$</td>
</tr>
<tr>
<td><img src="image2" alt="Symbol B" /></td>
<td>“Or” Type: Scenario $s_j$ or scenario $s_j$ happens, $s$ can happen, that is ${s_i = 1 \text{ or } s_j = 1} \rightarrow u_s = 1$</td>
</tr>
</tbody>
</table>

Table 2. Bayesian network transformation rules.

<table>
<thead>
<tr>
<th>$s_i$</th>
<th>$s_j$</th>
<th>$s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
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<td>1</td>
<td>1</td>
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</tr>
</tbody>
</table>

Scenarios Conversion Probability

Suppose $s$ is to be assessed scenario, conversion probability $p_u$ is the possibility of scenario $s$, the formulization is $p_u = p(s = 1)$. The scenario $s$ isn’t isolate. Its occurrence probability depends on the relationship of Bayesian network in each moment. Let scenario set is $S$ which includes $n$ scenarios, namely $S = \{s_1, s_2, \cdots, s_n\}$. These scenario attributes are changing over time, and the attribute of scenario $s_i$ at $t$ is $s_i(t)$, so $S(t)$ is the set which join in the time variable $s_i(t)$. Due to the development of natural disaster is irreversible and the scenario state of time $t+1$ only reply on the scenario state of time $t$, research problem accords with the Markov model, that is the probability distribution of $s$ at time $t+1$ only relates to the state of $s$ at time $t$ which can express as Eq. 1.

$$p(s(t+1)| S(0), S(1), \cdots, S(t)) = p(s(t+1)| S(t)) \quad \text{(1)}$$

So on in a similar fashion, the attribute state of $S(t)$ relates to the attribute state of $S(t-1)$, so calculation of conversion probability is an iterative process. It needs define the prior probability and conversion probability to establish the dynamic Bayesian network.

1. Prior network $B_0$, which show the distribution of the initial state.
2. Conversion network $B \rightarrow$, which show the conversion probability $p(s(t+1)| S(t))$ at each time $t$.

In fact, the deduction process of natural disaster is in a certain time range. In finite time interval $[0, T]$, the parent node of $S_i(0)$ is prior network $B_0$, and the parent node of $s(t+1)$ is scenario set at every time, so we can get the conditional probability distribution in similar way and confirm the conversion probability of scenario.

$$p_u = p(s(t+1) = 1) = p(S(0)) \prod_{t=0}^{T} p(S(t)| S(t-1)) \quad \text{(2)}$$

Among them, the scenario $S(t-1)$ is composed of multiple scenario factors, namely:

$$S(t-1) = \{s_1(t-1), s_2(t-1), \cdots s_i(t-1)\} \quad \text{(3)}$$

Then
\[ p(s_i(t) \mid s_j(t-1)) = \frac{p(s_j(t-1) \mid s_i(t)) p(s_i(t))}{\sum_{i=1}^{n} p(s_j(t-1) \mid s_i(t)) p(s_i(t))} \]

**Use Case Study**

Because of the adjacent to the coast of city A, it always suffers from typhoon disaster and has a big typhoon disaster in 2014, the scenario conversion as seen in Figure 3.

![Figure 3. Typhoon disaster deduction path of city A.](image)

According to Markov chain rules, happen probability of scenario 4 is only related to the scenario 3 and not affected by the scenario 1 and scenario 2, known:

\[ p_{u} = p(s(t + \Delta T_{3}) = 1) = p(s(t + \Delta T_{3}) \mid S(t + \Delta T_{3})) = \frac{p(S(t + \Delta T_{3}), s(t + \Delta T_{3}))}{p(S(t + \Delta T_{3}))} \]

However, scene 3 occurrence probability depends on the previous scene, and S6 changes over time, so the situation between 3 from scene to scene before also can’t ignore the influence of 4, need to calculate in time order. In the Bayesian networks, there is no parent node scenario called the initial situation, namely, in Fig. 3 S1, S2 and S3, as lead to the causes of the formation of S4, need give S1, S2 and S3 prior distribution. Prior distribution probability value mainly depend on expert experience and the historical data, and take \( p(S_{1}(t + \Delta T_{1}) = 1 \cup S_{2}(t + \Delta T_{2}) = 1 \cup S_{3}(t + \Delta T_{3}) = 1) = 1 \). According to the formula of full probability, incidence of the S4 available situation as follows:

\[ p(S_{4}(t + \Delta T_{4}) = 1) = \sum_{i=1}^{3} p(S_{i}) p(S_{4} \mid S_{i}) \]

So on, the probability of scenario \( H_{4} \) at \( t + \Delta T_{4} \) time can be calculated, the prior probability and condition probability can be seen in Table 3.

<table>
<thead>
<tr>
<th>( S_{1} )</th>
<th>( S_{2} )</th>
<th>( S_{3} )</th>
<th>( S_{4} )</th>
<th>( S_{5} )</th>
<th>( S_{6} )</th>
<th>( S_{7} )</th>
<th>( S_{8} )</th>
<th>( S_{9} )</th>
<th>( S_{10} )</th>
<th>( S_{11} )</th>
<th>( S_{12} )</th>
<th>( H_{4} )</th>
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<tbody>
<tr>
<td>( P )</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
<td>—</td>
<td>0.3</td>
<td>0.2</td>
<td>0.26</td>
<td>0.68</td>
<td>0.31</td>
<td>0.45</td>
<td>0.73</td>
<td>0.15</td>
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<tr>
<td>( S_{4} )</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>—</td>
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<td>( H_{1} )</td>
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<td>—</td>
<td>0.8</td>
<td>0.7</td>
<td>0.8</td>
<td>0.6</td>
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<td>( H_{2} )</td>
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<td>—</td>
<td>0.2</td>
<td>0.4</td>
<td>0.3</td>
<td>0.6</td>
<td>0.3</td>
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<td>( H_{4} )</td>
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<td>0.3</td>
<td>0.5</td>
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<td>( H_{4} )</td>
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</table>
Result:
\[ p(H_3(t + \Delta T3) = 1) = 0.67; \]
\[ p(H_4(t + \Delta T4) = 1 | H_3(t + \Delta T3) = 1) = 0.7; \]

Then: \[ p(H_4(t + \Delta T4) = 1) = 0.49. \]

The probability of scenario \( H_4 \) is 0.49 that is the conversion probability of \( H_3 \) to \( H_4 \). Its value is higher than the normal which imply more possible to generate scenario conversion, so it is necessary to combine with professor experience and make appropriate decision in order to prevent the occurrence of scenario \( H_4 \).

**Conclusion**

Aiming at the shortcomings of the static Bayesian network, this paper uses dynamic Bayesian network to estimate the scenario conversion probability, and analyzes scenario conversion paths to support the prediction, management and decision of natural disaster. Taking the disaster factors as the clue, we only analyze the scenario deduction process of natural disaster, and ignore the influence of hazard-affected bodies to the process. So in the future research, the interaction relationship between natural disaster and hazard-affected bodies to establish a complete deduction system of natural disaster scenarios.

**Acknowledgement**

Foundation Project: Emergency Management Major Research Project (91024028); General Program (71774043) supported by National Natural Science Foundation of China.

**References**


