The Modeling of Fire Scenario Deduction in Commercial Complexes by Bayesian Network

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Abstract: The fire evolution process in commercial complex buildings is complicated, and it is often difficult for firefighters to take targeted emergency measures when a disaster occurs. In order to solve this problem effectively, this paper combines Bayesian network with scenario deduction to deduce the evolution path of fire accidents in commercial complex buildings. On the basis of specifying the scenario deduction elements, the Bayesian network joint probability distribution is used to calculate the scenario state probability, so as to obtain the current state of the accident and the possible future evolution trend. The example results show that the model can directly show the fire evolution process of commercial complex, and provide a reliable basis for fire emergency decision-makers to take timely and effective emergency plans.

1 INTRODUCTION

The rise of commercial complex buildings has brought convenience to people's lives, but the complex architectural structure of the commercial complex and the dense combustible materials in these buildings also lurk a huge fire hazard. The unique regional environment of the commercial complex makes the evolution of fire highly uncertain and chain dynamic, and once a fire occurs in the area, people's lives and property safety will be greatly threatened. Therefore, how to quickly predict the fire evolution path based on the fire information and take early measures to reduce disaster losses after a commercial complex fire has become the focus of current research.

In recent years, scenario deduction model has been used to predict disaster accident trends in a wide range of fields, including natural disasters (Zhu, Li and Wang 2016), food safety (Song, Liu, Jiang and Yang 2018), production accidents (Wang, Zhang, Ji 2020, Li, Xia, WU 2014), and electrical safety (Lin, LYU, Wang, Peng 2019). Therefore, if the evolutionary path of fire in commercial complexes can be predicted by scenario deduction model, the result of this model can be used to design effective measures to control the growth and spread of fire in complex buildings, so as to improve the safety of life and property damage. In the earlier studies, the Bayesian network (BN) (Wu, Tan, GAI 2016), multidimensional scenario space methods (Qian, Liu, Jiao 2015) and knowledge meta-model (Zhang, Wang, Chen 2016) were combined with scenario deduction model. After analyzing the fire evolution law of commercial complex, this paper used the Bayesian network and scenario deduction model to construct the fire scenario evolution network, and then used the joint probability distribution of Bayesian network to calculate the scenario occurrence probability to realize the extrapolation of fire accidents in commercial complex.

2 FUNDAMENTALS OF SCENARIO DEDUCTION MODEL

Scenario evolution is used to provide an objective description of the current and possible future evolution of a disaster incident. Scenario deduction is a dynamic process, and after the initial event, other secondary events are often chained due to human interference and external environmental factors. Therefore, when the fire scenario evolution process of a commercial complex is extrapolated, the evolution of the fire scenario will be more intuitively

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grasped. To describe the process of scenario evolution, firstly, it is necessary to clarify the current state of the disaster event and the information of the accident scene, and then infer the evolution route and possible consequences of the event by objective and scientific means.

2.1 Elements of Scenario Deduction Model

To reflect the real situation of disaster evolution, emergency decision makers should first extract the key scenarios of a disaster that can describe the disaster situation in a certain time period. In the deduction of fire scenarios in commercial complex buildings, the key scenarios are the real fire situations faced by fire fighting and rescue decision makers. In the scenario evolution process, in addition to identifying the key scenarios in an accident, the emergency environment in which the scenarios are located and the measures taken by emergency decision makers for each scenario are also identified. Therefore, the commercial complex fire scenario evolution process contains four main elements: situational state, emergency measures, emergency environment, and evolution of the situation. The evolutionary network is established using a symbolic language to characterize the relationship between the elements, as shown in Figure 1.

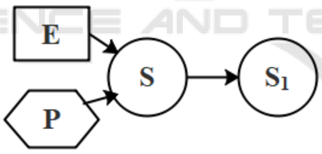

Figure 1: Basic units of scenario evolution.

S denotes the current situational state; P denotes the emergency measures to be taken in this situational state S; and E denotes the current environmental situation of the fire, i.e., the emergency environment. Under the influence of fire emergency measures and the emergency environment, scenario S will change and then jump to scenario S_1, which is a scenario unit of scenario evolution.

2.2 The Law of Scenario Deduction

The complexity of the fire disaster evolution process is determined by the specificity of the regional system of commercial complexes. In addition to the evolution of the fire accident scenario itself, the correlation between the systems, the complexity of the emergency environment, the effectiveness of emergency measures and other factors often cause the chain evolution of other secondary hazards, eventually forming an evolutionary network of multiple paths. As shown in Figure 2, the scenario S_1 appears in the commercial complex building at the moment t_1, and S_1 evolves to S_2 under the joint action of the emergency environment E_1 and emergency measures P_1. As time advances, the dynamic evolution of the scenario goes from the initial scenario S_1 through a series of evolutionary scenarios S_2, S_3… S_{n-1} and finally reaches the termination scenario Sn.

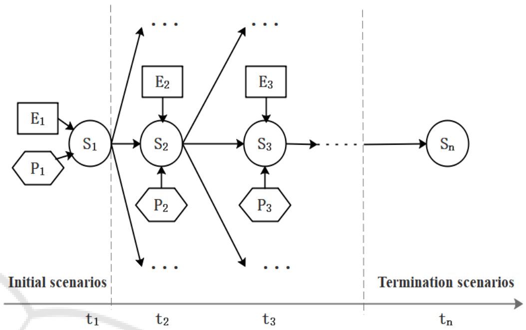

Figure 2: Scenario deduction rule.

3 FUNDAMENTALS OF BAYESIAN NETWORK

A Bayesian network is a directed acyclic graph representing probabilistic dependencies among variables, consisting of nodes representing variables and directed edges connecting these nodes. Bayesian, as a probability-based uncertainty inference method, is an important tool for dealing with uncertain information. Due to the complex building environment of commercial complexes and the changeable path of fire evolution process, it is more practical to use Bayesian network to simulate the fire evolution process.

3.1 Construction of Bayesian Network

When a fire broke out in a commercial complex, the current scenario of the incident was identified. However, the real scenario of the fire keeps changing over time. This paper extracts key scenarios and influencing factors by combining the experience of experts in the field and the law of fire evolution in commercial complexes, and then the evolution network is established by symbolic language. In this paper, nodes are used to represent the key elements in the evolution process, and directed edges are used to represent the influence of each element on the scenario state and the scenario evolution, so as to construct the Bayesian network of the fire scenario evolution process of commercial complex. As shown in Figure 3, the nodes S_1, S_2, S_3 respectively denote different situations, $P(S_1)$ represents the prior probability of the occurrence of node S_1, $P(S_2)$ represents the prior probability of the occurrence of node S_2, $P(S_3, S_1)$ and $P(S_3, S_1)$ respectively represent the conditional probability of node S3 occurrence when scenarios S_1 and S_2 occur.

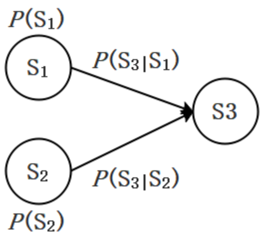

Figure 3: Sketch of Bayesian networks.

3.2 Determination of Bayesian Network Probabilities

Determining the Bayesian network also identifies various scenarios that may occur in the future, but it's also necessary to know the probabilities of occurrence of these scenarios in order to achieve inference about the evolution of the scenarios. The Bayesian network inference is based on Bayesian probability theory. Firstly, the prior probability of the initial scenario should be determined based on the local historical statistics of this type of accident and the expert's own experience, and then synthesize each expert's opinion to analyze the degree of association between nodes. Finally, the conditional probability is derived according to the pessimistic decision criterion. Then, the state probabilities of the nodes in the network are calculated using the Bayesian network joint probability formula.

The joint probability formula of Bayesian network is as follows:

$$P(S_1, S_2, \cdots, S_n) = P(S_n|S_1, S_2, \cdots, S_{n-1}) \cdots P(S_2|S_1)P(S_1) = \prod_{i=1}^{n} P[S_i|P_a(S_i)] \quad (1)$$

In the form, $P_a(S_i)$ is denote the prior probability of the parent node of S_i, $i = 1, 2, \cdots n$.

4 CASE STUDY

In 2013, a commercial complex was affected by an underground natural gas pipeline leak, which caused a fire and explosion on the first basement and first floor of the building, which quickly spread to the roof and nearby buildings. In this paper, scenario deduction and analysis of the accident were conducted by using the above-mentioned method.

4.1 Analysis of the Evolutionary Process of Accident Scenarios

Based on the information of the commercial complex

Table 1: Scenario elements of the fire accident in commercial complex.

Situational state (S)	Emergency environment €	Emergency measures (P)
A fire broke out on the first underground floor **(S_1)**	gas pipelines leakage **(E_1)**	Emergency treatment of employees **(P_1)**
The fire was controlled without spreading on the first underground floor **(S_2)**	There were many combustibles in the building **(E_2)**	Firefighters put out the fire **(P_2)**
The end of the fire accident **(S_3)**		
Fire spread to upper floors **(S_4)**	Surrounding roads were blocked **(E_4)**	Request support to stop the fire from spreading **(P_4)**
Fire was basically stable under control **(S_5)**	Sending more people to rescue **(E_5)**	Firefighters put out the fire **(P_5)**
The end of the fire accident **(S_6)**		
Open flame extinguished **(S_7)**	Large fire smoke **(E_7)**	Firefighters put out the fire **(P_7)**
The end of the fire accident **(S_8)**		
The whole building was in fire and endangered the surrounding buildings **(S_9)**	Smaller spacing between surrounding buildings **(E_9)**	Firefighters put out the fire **(P_9)**
Surrounding buildings fire extinguished **(S_{10})**	Open flame in the complex continues to spread outward **(E_{10})**	Adding large equipment to extinguish fire **(P_{10})**
Open flame in the complex extinguished **(S_{11})**	Large fire smoke **(E_{11})**	Firefighters put out the fire **(P_{11})**
The end of the fire accident **(S_{12})**		

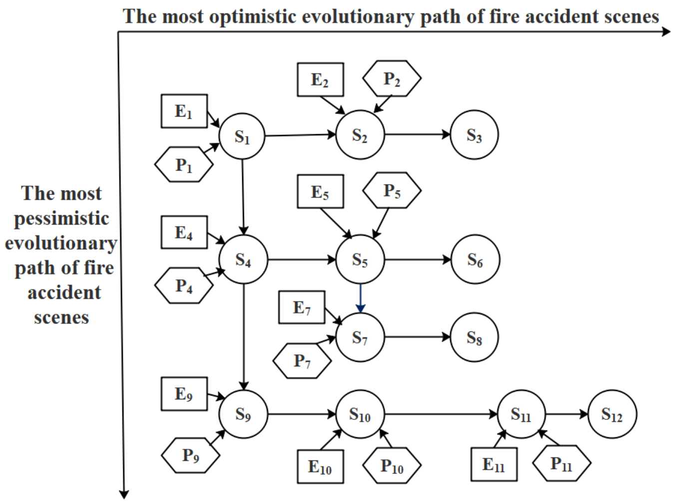

Figure 4: Schematic diagram of the Bayesian network scenario deduction path.

Table 2: Network nodes prior probability and conditional probability table (partial data).

Node	prior probability	conditional probabilities
S1	$P(E_1=T)=0.95$ $P(P_1=T)=0.15$	$P(S_1=T \mid E_1=T,P_1=T)=0.70$ $P(S_1=T \mid E_1=T,P_1=F)=0.95$ $P(S_1=T \mid E_1=F,P_1=T)=0.40$ $P(S_1=T \mid E_1=F,P_1=F)=0.60$
S2	$P(E_2=T)=0.95$ $P(P_2=T)=0.45$	$P(S_2=T \mid S_1=T,P_2=T,E_2=T)=0.50$ $P(S_2=T \mid S_1=T,P_2=T,E_2=F)=0.60$ $P(S_2=T \mid S_1=T,P_2=F,E_2=T)=0.10$ $P(S_2=T \mid S_1=T,P_2=F,E_2=F)=0.15$ $P(S_2=T \mid S1=F,P_2=T,E_2=T)=0.75$ $P(S_2=T \mid S1=F,P_2=T,E_2=F)=0.90$ $P(S_2=T \mid S1=F,P_2=F,E_2=T)=0.65$ $P(S_2=T \mid S1=F,P_2=F,E_2=F)=0.70$

fire accident scene, the accident was sorted out according to the time line. Through the communication with experts, the key Situational State (S), emergency environment (E) and Emergency measures（P）were extracted from each key period in the accident development process, as shown in Table 1. After each node of the Bayesian network were determined, the nodes could be connected by directed edges to form the accident scenario deduction path, as shown in Figure 4.

According to the fire environment and the effectiveness of firefighting and rescue measures, the fire evolution of commercial complex is divided into optimistic and pessimistic paths. The horizontal arrow indicates that the firefighting and rescue is more effective, and the scenario evolves in the optimistic direction. The vertical arrow represents the opposite meaning. In the figure, $S_1 \rightarrow S_4 \rightarrow S_9$ is the most optimistic direction in the evolution path of fire scenarios, and $S_1 \rightarrow S_4 \rightarrow S_9$ is the most pessimistic path.

4.2 Calculating the Probability of Each Scenario

To deduct the fire accident of the commercial complex, it is necessary to determine the probability of each scenario. The prior probability of network

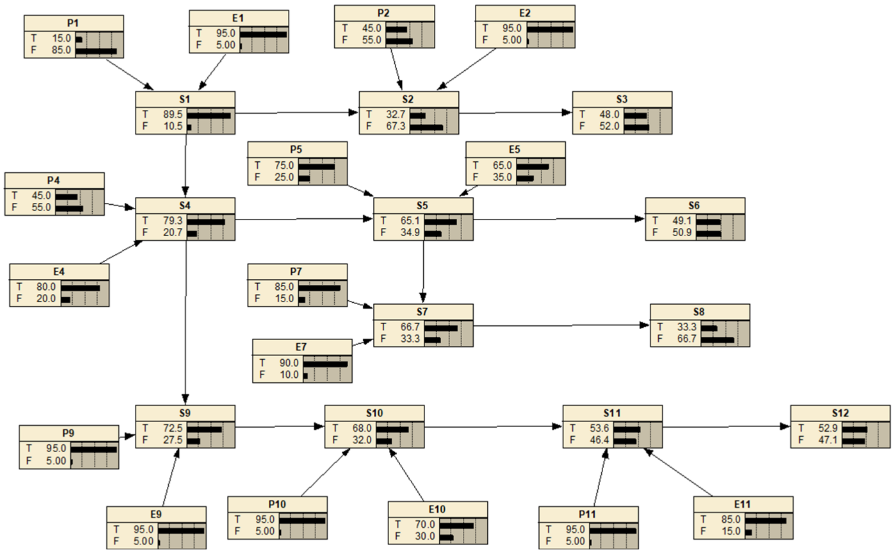

Figure 5: Fire accident dynamic Bayesian network situation deduction diagram.

nodes were scored by experts in the field based on historical statistics of complex fires and their own experience, then combined with the accident scenario evolution model described above, and finally the conditional probabilities were derived based on pessimistic decision criteria (Table 2).

Bayesian network joint probability formula is used to calculate the state probability of each scenario. For example, the state probability $P(S_1 = T) = P(E_1 = T) * P(P_1 = T) * P(S_1 = T \mid E_1 = T, P_1 = T) + P(E_1 = T) * P(P_1 = F) * P(S_1 = T \mid E_1 = T, P_1 = F) + P(E_1 = F) * P(P_1 = T) * P(S_1 = T \mid E_1 = F, P_1 = T) + P(E_1 = F) * P(P_1 = F) * P(S_1 = T \mid E_1 = F, P_1 = F) = 0.895$, and state probability of other scenarios can be calculated by analogy with this method. This paper used the Bayesian network software Netica to obtain the Bayesian network scenario deduction diagram of fire accident in the commercial complex, as shown in Figure 5.

4.3 Analysis of Inference Results

(1) It can be seen from Figure 4 that the scenarios with a higher probability of occurrence were S_1, S_4 and S_9, with the occurrence probability of 89.5%, 79.3% and 72.5% respectively. It could be seen that the probability of the accident scenario evolution in an adverse direction was higher than that of the optimistic direction. However, this does not mean that fire emergency measures were ineffective. To some extent, these measures had played a role in delaying the spread of fire.

(2) After the occurrence of disaster, taking effective measures in time has a certain inhibitory effect on the evolution of the disaster. While other conditions remained unchanged, when the probability of P_1 was increased to 95%, the probability of S_1 was reduced from 89.5% to 69.7%; the probability of S_2 has been reduced from 79.3% to 69.9%. In the early stage of the commercial complex fire accident, if the managers took effective emergency measures immediately, such a big disaster loss would not have been caused.

5 CONCLUSION

In this paper, the derivation of the evolutionary path of fire accidents in commercial complexes includes three processes: (1) analyzing the evolutionary law of accident scenarios; (2) constructing a Bayesian scenario network; (3) calculating the scenario state probabilities. According to the example results, it can be found that the calculation results are basically consistent with the actual situation of the fire scene, which verifies the validity of the model.

This paper provides a new perspective for firefighters to develop scientific emergency response plans by using scenario extrapolation models to predict fire evolution paths. The method can provide a more intuitive response to the effect of emergency measures and facilitate timely adjustment of the plan by firefighters. However, due to the complex fire environment of commercial complex buildings and the uncertainty of path development, this paper only considers the evolution path with fire development as the main line, and a more comprehensive, systematic and reasonable analysis of evolution path needs further study.

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