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Fire Risk Assessment in Universities Based on Fault Tree Analysis and Bayesian Network

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ABSTRACT

In order to scientifically and accurately analyse the fire hazards existing in colleges and universities, and put forward feasible suggestions for eliminating hidden dangers, a fire risk assessment method based on Fault tree analysis and Bayesian network is proposed. Firstly, the Fault tree of the large loss caused by the fire in the university premises is constructed, and then the Fault tree is transformed into a Bayesian network model. In this method, the failure risk of the fire protection system can be obtained by forward reasoning according to the probability of the basic events in the fire, and finally, the reliability of the fire protection system of the whole university is analysed. At the same time, combined with the reverse diagnosis and reasoning technology of Bayesian network, according to the known or assumed state of leaf nodes, the posterior probability and probability importance degree of each root node can be reversed to check the weak links in the fire protection system. In the conclusion, suggestions and rectification strategies are put forward for the fire protection system in colleges and universities. This paper proposes a method that combines fault tree analysis with Bayesian network and applies it to fire risk assessment in colleges and universities. Based on the fire protection big data, the software Genie3.0 is used to construct a Bayesian network model of fire risk in universities, and an example analysis of fire risk assessment is carried out by taking a university in Nanjing as an example, which not only analyses the reliability of the entire system, but also It also uses the bidirectional reasoning ability of Bayesian network to analyse the weak link performance of the system, which improves the model's description ability and inference computing ability. It is proved that the FTA-BN method has application potential in the field of fire risk assessment.

Keywords: Fire risk assessment, Fault tree analysis, Bayesian network, Probability importance degree

INTRODUCTION

Major fire accidents happened frequently in colleges and universities, causing great losses to the life and property safety of teachers and students. The university areas has the typical characteristics of large density of personnel, combustible materials, electrical appliances and large power load, which has a large fire hazard. The causes of college fire accidents are not only complex and diverse, but also the composition of fire protection system. It is difficult to get a reliable assessment of fire risk by using traditional analytical methods.

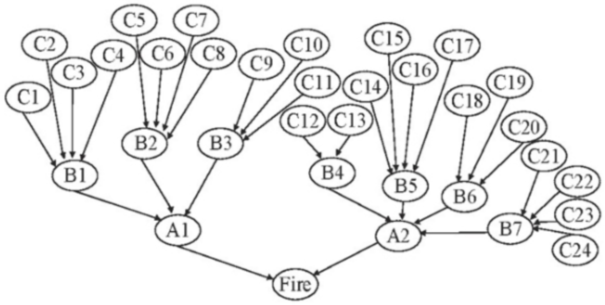

Figure 1: Illustration of Bayesian Networks.

Among the qualitative methods, Fault Tree Analysis (FTA) is a commonly used safety engineering decision-making method, also known as fault tree analysis. Its manifestation is a special directed logic tree. The fault tree analysis adopts the deductive analysis method, starting from the specific accident or fault to be analysed (i.e., the top event). The analysis is carried out layer by layer until all the underlying causes of the accident (i.e. the underlying events) are identified. Accident tree analysis can not only directly and clearly show all kinds of basic events that cause accidents, but also clearly show the nature and mechanism of accidents. It is widely used in safety evaluation, reliability analysis, accident investigation and other fields.

Bayesian Network (BN) is a directed acyclic graph, which is composed of nodes representing variables and directed edges connecting these nodes. Nodes represent random variables, and the directed edges between nodes represent the mutual relationship between nodes. The parent node points to its child node, and the strength of the relationship is expressed by conditional probability. If there is no parent node, the information is expressed by prior probability. The Bayesian network also has the characteristics of bidirectional derivation. The posterior probability of the root node can be obtained according to the result, and the cause can be deduced from the result. Bayesian network analysis is applicable to the expression and analysis of uncertain and probabilistic events, and can be inferred from incomplete, inaccurate or uncertain knowledge or information. It is very suitable for the analysis of fire and firefighting complex system.

Xu Jianqiang et al. (2019) introduced Bayesian network analysis method into the quantitative fire risk assessment and proposed a fire dynamic risk assessment model based on Bayesian networks. Zhang Lining et al. (2015) analysed the uncertainty and characteristics of fire occurrence in high-rise civil buildings, and studied the comprehensive assessment model suitable for fire risk assessment of high-rise civil buildings. Zhang Qiang et al. (2016) built a fire shaft analysis model based on Bayesian network. How to further ensure the BN risk assessment method of science and rationality, to ensure the assessment results accurate, effective and objective, is the current BN fire risk assessment method of the main research direction.

Bayesian networks based on conditional probability are more suitable for fault analysis and judgment of complex systems. BN and FTA are very similar in terms of reasoning mechanism, system state description, expressions

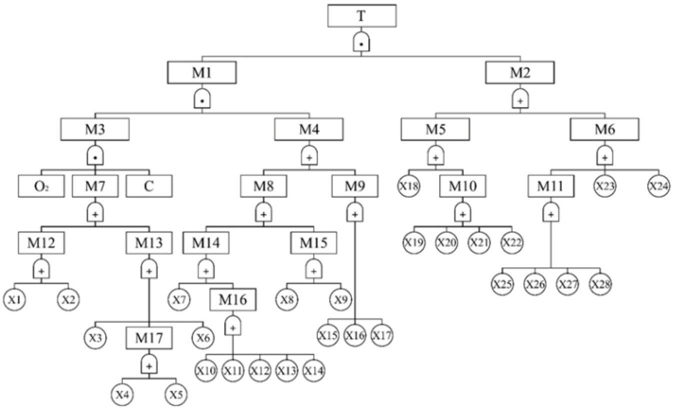

Figure 2: University Area Fire Risk Accident Tree.

form and so on (Ma et al, 2021). Compared with FTA, BN has the ability to describe event polymorphism and the uncertainty of fault logic relationship. However, the construction of Bayesian network structure depends on the professional knowledge of domain experts, which is the biggest constraint in the application process of Bayesian network (Gong et al, 2009). Therefore, the construction of Bayesian network based on the fault tree analysis is an effective and effective method, which has been widely used in the field of fault diagnosis. Zheng et al. (2019) built BN based on the established fault tree and developed a comprehensive fault diagnosis system.

Inspired by the above research, this paper adopts the scheme of transforming accident tree model to Bayesian network, and applies it to the field of fire risk assessment for the first time, and proposes a fire risk assessment method in colleges and universities based on FTA and BN.

University Fire Risk Accident Tree

For the whole fire accident system, the top event usually causes great consequences for college fire accident. The most important thing to be considered in college fire accidents is the life safety of teachers and students. Therefore, it focuses on the analysis of fire occurrence and ineffective personnel evacuation. For the direct cause of these two factors, it is defined as the intermediate event of the system, and then the intermediate event is decomposed into the bottom event that can't be divided and preferably recorded with data.

In the fire risk accident tree, logic gate and gate indicate that only when all the events of the previous step occur will the output events of the next step be led to. For example, the occurrence of fire and insufficient evacuation together lead to heavy losses in fire accidents. Logic gate or gate indicates that any event will lead to the occurrence of the next level of events. For example, open fire source and electrical fire source can constitute the ignition source of fire, and connect events with appropriate logic gate. The university fire risk accident tree is built based on the above rules, as shown in Figure 2. Table 1 shows the relationship between symbols and events in the accident tree.

The example data in this paper comes from the routine inspection data of a university in the fire management system. The unit will carry out routine

Table 1. Incident tree event mapping table.

Code	Name	Code	Name
T	College fire causes heavy damage	X6	High power electrical breakdown circuit
M1	Expansion of fire	X7	Students can't use fire-fighting facilities
M2	Unfavorable evacuation	X8	Fire extinguishing effect of fire brigade was ineffective
M3	Outbreak of fire	X9	fire brigade was late in arriving
M4	Fire was not effectively contained	X10	Fire extinguishing equipment failure
M5	Evacuation capacity is insufficient	X11	The layout of fire-fighting facilities is unreasonable
M6	Building evacuation capacity is insufficient	X12	Insufficient fire supply
M7	Source of ignition	X13	Self-injection system failed
M8	Poor fire extinguishing ability of buildings	X14	Self-alarm system failed
M9	Building fire resistance is poor	X15	Structure of the building is not reasonable
M10	System management is not in place	X16	Fire resistance of the building is not enough
M11	Building structure is not reasonable	X17	Unreasonable division of fire protection zones
M12	Open flame source	X18	Fire drill is not in place
M13	Electric ignition source	X19	Personnel safety awareness is weak
M14	Not in time to save themselves	X20	Lack of management and coordination ability
M15	Ineffective fire brigade	X21	Enforcement of fire regulations is not in place
M16	Failure of fire service	X22	Emergency plan is not in place
M17	Line fire	X23	Excessive personnel density
X1	Cigarette and common sources of ignition	X24	Building smoke exhaust system failed
X2	Use an open flame	X25	No evacuation instructions or unclear
X3	lightning strike	X26	The number of safety exits is less
X4	Aging of line	X27	Distance to safety is too long
X5	short circuit	X28	Evacuation path is too narrow

inspection on the fire-fighting facilities, self-spraying system, alarm system, fire access and other items in the unit. If it is qualified, it is considered to be up to the standard. If it is not up to the standard, both inspection timeout and missed inspection are considered as not up to the standard. That is, the basic event is invalid in the system. For basic events that do not appear in the inspection items, such as abstract events such as inadequate implementation of fire control regulations and indifference of fire control awareness, the probability is determined by literature review and hierarchical tomographic method. Fire risk fault tree in colleges and universities can clearly reflect the cause of system failure, but it can only reason the fault tree itself in a top-down order, and the reasoning efficiency is not high (Hu L, 2020). Therefore, it is necessary to transform the accident tree to Bayesian network.

Bayesian Network

A. Transformation of accident tree to Bayesian network

As for the accident tree model and Bayesian network, both have their limitations when applied. Compared with other reliability evaluation methods such as accident tree analysis, Bayesian network has the ability to process uncertain information and its unique bidirectional reasoning mechanism (Guo J, 2019).

The transformation process from FTA to BN is shown in Figure 3. The structure of the accident tree model corresponds to that of the Bayesian network. The bottom event of the accident tree corresponds to the root node of the system failure Bayesian network. The connections between the risk events of the accident tree correspond to the edges between the Bayesian network nodes. The construction of Bayesian network on the basis of accident tree can effectively reduce the construction difficulty of Bayesian network, and the combination of fault tree can improve the description ability of Bayesian network model (Bingyu You, 2019).

B. Establishment and reliability analysis of Bayesian network for fire risk in colleges and universities

According to the above steps to establish the university fire risk Bayesian network, the network is constructed by GENIE3.0 software. The Bayesian network for college fire risk assessment is shown in Figure 4. The names of university fire risk Bayesian network nodes are shown in Table 2.

The state of the root node in Bayesian network has uncertainty, but it has no parent node, so conditional probability cannot be used to describe the state probability of the root node. In Bayesian statistical inference, prior probability is used to express the state confidence of the root node. According to the above, the failure probability of each bottom event in the accident tree is assigned to the corresponding root node in the fire risk Bayesian network. The prior probability to becoming the root node. The results are shown in Table 3.

The conditional probability distribution of the middle nodes of the Bayesian network also has an important effect on the final result of the network. In FTA-BN method, the conditional probability distribution is determined according to the corresponding logical relation between events. That is, edges in the network correspond to logical gate meanings in the accident tree. For example, in the conditional probability distribution of a Bayesian network or gate, where x_1, x_2, and x_3 are the inputs of the OR gate, and x_4 is the output, the conditional probability distribution of the Bayesian network is as follows.

$$P(y_4 = 1|x_1 = 0, x_2 = 0, x_3 = 0) = 0, P(x_4 = 1|\text{else}) = 1 \quad (1)$$

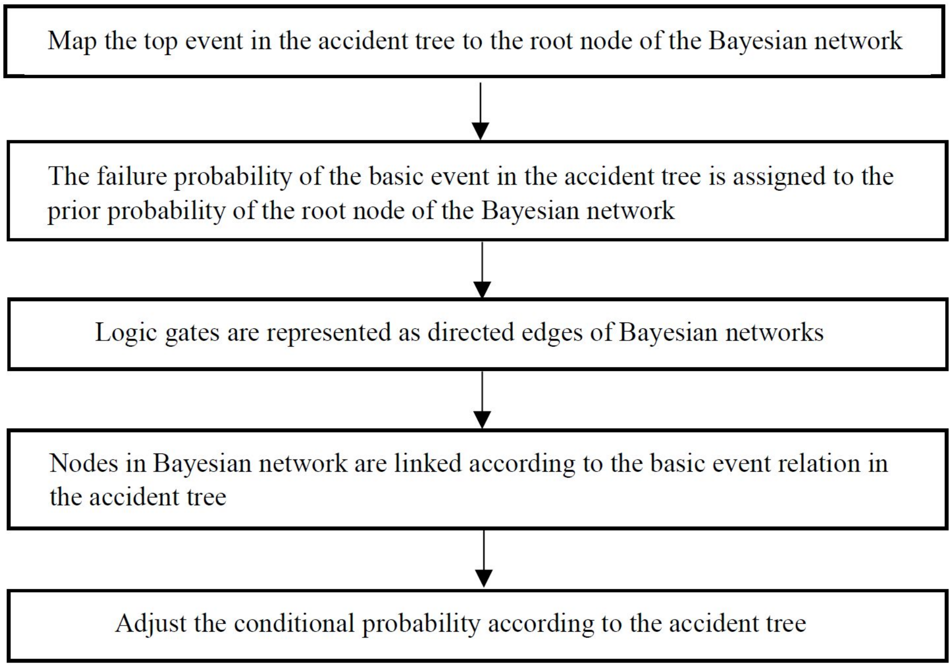

Figure 3: Step of transformation of FTA-BN.

If y_1, y_2 and y_3 are the inputs of and gate, and y_4 is the output, the conditional probability distribution of their corresponding Bayesian networks is as follows.

$$P(y4 = 1|y1 = 1, y2 = 1, y3 = 1) = 1, P(y4 = 1|\text{ else}) = 0 \quad (2)$$

Through the prior probability and conditional probability distribution of the corresponding nodes on the Bayesian network of fire risk, we can calculate the probability of major fire accident, namely the reliability of the whole system. The probability of system failure top event T is calculated by the following formula.

$$P(T = 1) = \sum_{F_1, F_2, \cdots, F_{n-1}} P(F_1{=}f_1, F_2{=}f_2, \cdots, F_{n-1}{=}f_{n-1}, T = 1) \quad (3)$$

In Formula (3), the major loss caused by fire in colleges and universities is the top event T; F_i is the intermediate event and the bottom event of the system; f_i represents the occurrence of risk event F_i; n is the number of nodes in the Bayesian network of system failure.

According to the calculation, the possibility of major losses caused by fire in this university is 5.609%, and according to the probability of system failure, the reliability of this university fire control system is about 94.391%.

$$\mathrm{R} = 1 - \mathrm{P}\,(\mathrm{T} = 1) = 1 - -0.05609 = 0.94391 \quad (4)$$

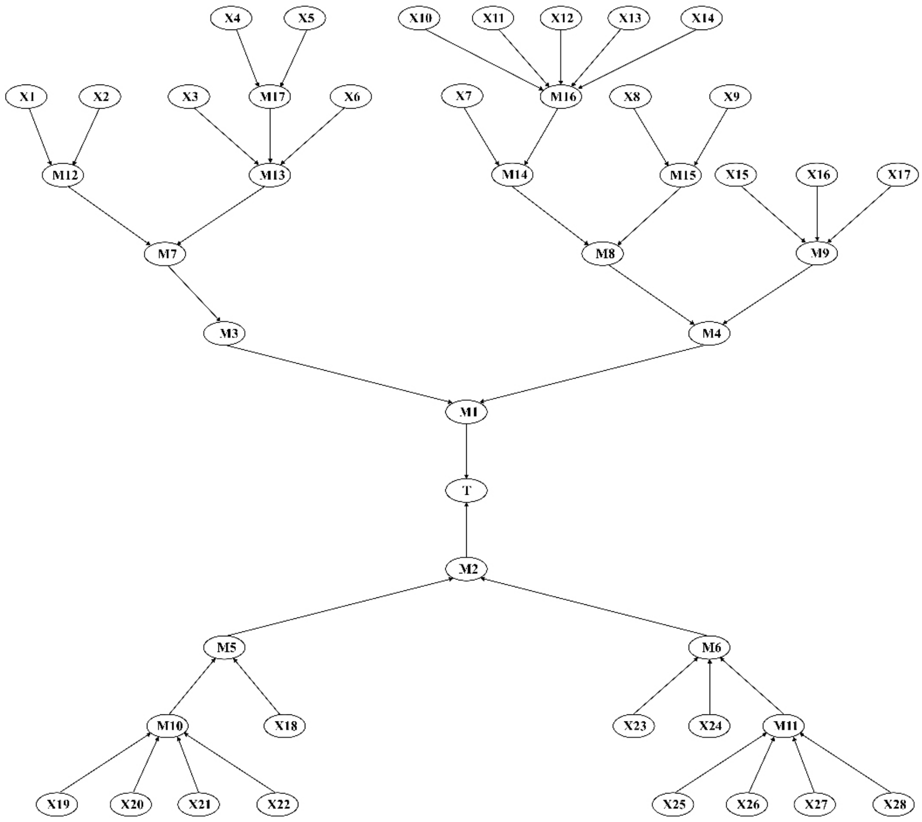

Figure 4: Bayesian Fire Networks in Colleges and universities.

C. Diagnosis and analysis of causes of college fire based on Bayesian network

According to the above, Bayesian network has the characteristics of bidirectional reasoning. By analysing from the root node upwards, the influence degree of risk events on system operation can be analysed, and the occurrence probability of other event nodes in the system can be calculated, namely the posterior probability of risk events. The calculation formula is as follows:

$$P\left(F_i = 1 \middle| F_j = 1\right) = \frac{\sum_{F_1,\ldots F_n} P\left(F_k = f_k, F_i = 1, F_j = 1\right)}{P\left(F_j = 1\right)} (1 \le k \le n, k \ne i, j) \quad (5)$$

In Formula (5), F_i is the intermediate event and the bottom event of the system, f_i indicates whether the risk event F_i occurs, and n is the number of nodes in the system failure Bayesian network.

In Bayesian networks, both upward reasoning and downward diagnosis can be made by using the known information of nodes. Therefore, compared with only using fault tree analysis, the transformed system failure Bayesian network has more flexible and effective analysis ability (Runfeng Cao, et al, 2022). The concept of probability importance is introduced.

The contribution degree of the minimum cut set to the occurrence of the top event is called the significance degree. In the established system failure

Table 2. Name of a Bayesian network node.

Code	Name	Code	Name
T	College fire causes heavy damage	X6	High power electrical breakdown circuit
M1	Expansion of fire	X7	Students can't use fire-fighting facilities
M2	Unfavorable evacuation	X8	Fire extinguishing effect of fire brigade was ineffective
M3	Outbreak of fire	X9	fire brigade was late in arriving
M4	Fire was not effectively contained	X10	Fire extinguishing equipment failure
M5	Evacuation capacity is insufficient	X11	The layout of fire-fighting facilities is unreasonable
M6	Building evacuation capacity is insufficient	X12	Insufficient fire supply
M7	Source of ignition	X13	Self-injection system failed
M8	Poor fire extinguishing ability of buildings	X14	Self-alarm system failed
M9	Building fire resistance is poor	X15	Structure of the building is not reasonable
M10	System management is not in place	X16	Fire resistance of the building is not enough
M11	Building structure is not reasonable	X17	Unreasonable division of fire protection zones
M12	Open flame source	X18	Fire drill is not in place
M13	Electric ignition source	X19	Personnel safety awareness is weak
M14	Not in time to save themselves	X20	Lack of management and coordination ability
M15	Ineffective fire brigade	X21	Enforcement of fire regulations is not in place
M16	Failure of fire service	X22	Emergency plan is not in place
M17	Line fire	X23	Excessive personnel density
X1	Cigarette and common sources of ignition	X24	Building smoke exhaust system failed
X2	Use an open flame	X25	No evacuation instructions or unclear
X3	lightning strike	X26	The number of safety exits is less
X4	Aging of line	X27	Distance to safety is too long
X5	short circuit	X28	Evacuation path is too narrow

Bayesian network, the state value of each node is two-state. Probabilistic significance degree is one of the importance degree, which can reflect the change degree of system failure caused by the change of factor state. In Bayesian networks, risk events with greater probability importance have greater impact on system reliability. Therefore, it is necessary to focus on prevention and optimization. The probability importance calculation formula of the root node of Bayesian network is.

$$I_i^{\mathrm{Pr}}(y_i) = P(T = 1|y_i = 1) - P(T = 1|\ y_i = 0) \tag{6}$$

Table 3. Bayesian network root node prior probability table.

Node	Prior probability	Node	Prior probability	Node	Prior probability
X1	0.05	X11	0.02	X21	0.02
X2	0.02	X12	0.02	X22	0.04
X3	0.01	X13	0.03	X23	0.05
X4	0.005	X14	0.01	X24	0.02
X5	0.005	X15	0.04	X25	0.01
X6	0.3	X16	0.04	X26	0.01
X7	0.05	X17	0.03	X27	0.01
X8	0.03	X18	0.1	X28	0.01
X9	0.02	X19	0.08		
X10	0.03	X20	0.03		

In Formula (6), $I_i^{\mathrm{Pr}}(y_i)$ is the difference between the top event probability value when y_i node takes 1 and the top event probability value when y_i node take 0. A posteriori probability and probability importance of 28 root nodes are calculated, and the data list will be obtained, as shown in Table 4.

Table 4 shows the ranking results of a posteriori probability and probability importance of basic events, so as to compare the impact of basic events on the whole system in fire, so as to effectively prevent and optimize weak links.

Among the results, X6, X8, X18, X19 and X23 are ranked at the top, indicating that the breakdown circuit of high-power electrical appliances, weak fire awareness, large population density, poor fire extinguishing effect of fire brigade and inadequate emergency plan preparation are the main causes of college fire. This suggests that colleges and universities should strengthen student management and avoid using high-power electrical appliances in dormitories and other areas with a huge power load. We should strengthen the training of teachers and students, strengthen the fire awareness, and prepare the fire emergency plan, so that we can be ready when the fire comes. Colleges and universities should also make reasonable plans to reduce the staff density. The fire brigade also strengthened the fire drill of the university area to enhance the fire extinguishing effect. In addition, for evacuation-related events such as X23, X24, X25, X26, X27, X28, the posterior probability ranks the bottom, but the probability importance ranks the top, indicating that evacuation is an indispensable factor in controlling the consequences of fire. In the planning of colleges and universities, the design of evacuation mode should be fully considered. Arrange reasonable and convenient evacuation channels, eye-catching evacuation prompts. Can greatly control and reduce fire damage.

CONCLUSION

(1) This paper presents a method of combining accident tree analysis with Bayesian network and applying it to fire risk assessment in colleges and universities. Based on the big data of fire protection, this paper uses Genie3.0 software to build the Bayesian network model of college fire risk, and takes a university in Nanjing as an example to carry out

Table 4. Ranking table of posterior probability and probability importance of root nodes in Bayesian networks.

Node	Posterior probability	Posterior probability sort	Probability significance	Probability significance sort
X1	0.1384	6	0.1044	13
X2	0.0554	17	0.1012	14
X3	0.0277	25	0.1002	15
X4	0.0138	27	0.0997	16
X5	0.0138	27	0.0997	16
X6	0.8304	1	0.1417	1
X7	0.1044	8	0.0643	19
X8	0.6265	2	0.0872	18
X9	0.0418	18	0.0623	27
X10	0.0627	12	0.0629	23
X11	0.0418	18	0.0623	25
X12	0.0418	18	0.0623	25
X13	0.0627	12	0.0629	23
X14	0.0209	26	0.0617	28
X15	0.0835	10	0.0636	20
X16	0.0835	10	0.0636	21
X17	0.0627	12	0.0629	22
X18	0.3084	3	0.1299	2
X19	0.2467	4	0.1271	3
X20	0.0925	9	0.1205	6
X21	0.0617	15	0.1193	7
X22	0.1234	7	0.1218	5
X23	0.1542	5	0.1230	4
X24	0.0617	15	0.1193	7
X25	0.0308	21	0.1181	9
X26	0.0308	21	0.1181	9
X27	0.0308	21	0.1181	9
X28	0.0308	21	0.1181	9

the example analysis of fire risk assessment. It is proved that FTA-BN method has potential application in the field of fire risk assessment.

(2) Bayesian network can deduce the conditional probability of occurrence of each node when the failure probability of risk events is known, which can reflect the possibility of system failure under a specific environment, and conduct quantitative analysis of the whole system. The comprehensive use of FTA and BN analysis methods can make use of strengths and avoid weaknesses, improve the system analysis ability, and quickly diagnose and analyse the fault problems of complex systems. It makes up for the disadvantages of FTA in complex system calculation. This method also makes use of prior knowledge and does not require high data quantity and quality.

(3) Due to the lack of historical accident data of some risk events and some abstract events that are difficult to quantify, the prior probability is obtained by fuzzy comprehensive evaluation method based on expert evaluation, which does not completely avoid the influence of human

subjectivity on the objectivity of the system. The follow-up work can be conducted on the basis of collecting historical accident data, building different analysis models for different accident scenarios, and proposing effective and reliable coping strategies.

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