Analysis of Wildfire Fault Based on F-FTA Method

Changkun Chen¹, ², *, Sai Cao¹, ² and Tong Xu¹, ²

¹Institute of Disaster Prevention Science and Safety Technology, Central South University, Changsha 410075, P. R. China
²State Grid Hunan Elect Power Corp, Disaster Prevent & Reduct Ctr, State Key Lab Disaster Prevent & Reduct Power Gri, Changsha 410007, Hunan, Peoples R China

*Corresponding author e-mail: cckchen@csu.edu.cn, ¹acshsca@163.com, ²tongxuxut@csu.edu.cn

Abstract. It is particularly necessary to prevent the occurrence of wildfires, which caused a series of economic losses and ecological disasters. In this paper, an evaluation model is established by the combination of Triangular Fuzzy Theory and FTA (F-FTA). Considering the human and environmental errors in the wildfire fault, the triangular fuzzy probability, error limits and importance degree of the events are adopted, and the causes of probability fluctuation and proper measures are raised. In addition, this model is applied in Zhaotong, Yunnan to analysis the potential risk of wildfires. The result shows that the triangular fuzzy probability of local wildfire fault is (0.0024, 0.021, 0.071), and the probability of wildfire occurrence fluctuates greatly. Especially, Sacrificial fire (X₁₈), Burning Charcoal (X₈), Burning woodland (X₉), Smoking in the wild (X₁₆), Burning pasture (X₁₀), Children playing with fire (X₂₀) exist highly risk. Therefore, fire-fighting equipment should be arranged flexibly, and individualized measures should be formulated in response to the accidental occurrence of wildfires to provide guidance for the prevention and control of wildfires faults.

1. Introduction

The forest ecosystem is complex with a wide series of plants and abundant forest resources, when subjected to extreme weather, ecological disasters and the economic losses caused by wildfires are enormous. In October 2017, 250 wildfires broke out in Northern California, burning 99,148 hectares and killing 44 people, the direct economic losses exceeded $9.4 billion, and the loss to the US economy is expected to reach $85 billion. In December 2017, there were 20 wildfires in Southern California with a burning area of 961 square kilometers, and the death toll was 2 and the direct economic loss exceeded 3.139 billion US dollars. In the autumn of 2018, a wildfire broke out in northern California, which spread rapidly under the influence of strong winds, becoming the third largest fire in California history. As of January 3, 2019, 71 people were killed and more than $19 billion were lost. It is necessary to pay attention to the research on wildfires accidents, because the wildfire fault not only causes losses to the economy [1], but also affects the normal life of the people.

The predecessors have done a lot of research on the prediction of wildfires, considering the objective natural conditions before the occurrence of wildfires to predict the wildfires, Franca G. et al consider the fire risk index, the remote sensing hotspot near the power line and the vegetation coverage to predict fire risk [2], Stambaugh M C. et al consider the micro-climate, physical and

[1] Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Published under licence by IOP Publishing Ltd
chemical fire frequency conditions to predict the probability of fire occurrence [3], Vaucchiano G. et al consider the seasonal and regional factors to predict the probability of fire occurrence of the alpine region [4]. The literature [5] uses the MESMA model to predict the restoration of forests after a fire. The cellular automata are coupled with the existing forest fire model to improve the prediction accuracy of forest fire spreading [6].

The predecessors established the evaluation model of wildfires, analyzing the risk of wildfires qualitatively: Wildfire Archive & Maxent model [3], the mixed FTA model [4] and the BRT model [7] established to evaluate the occurrence and recovery of wildfires. Before the occurrence of the fire, Xu K. et al establish the logistic regression model to estimate the probability of wildfires occurrence, and it was concluded that drought conditions and specific human activities are important factors [8]. Fang L. et al Consider the pre-fire vegetation, topography, and surface water to assess the severity of forest fires [9]. Reilly M J. et al consider forest structure projections (tree size and canopy cover) and remote sensing combustion level map to study wildfire dynamics cumulative impact [10]. When the wildfire occurs, the fire-fighting facilities and firefighters are dynamically adjusted to reduce the damage [11].

In summary, the previous studies have made certain achievements from the perspectives of forecasting and early warning, risk assessment and so on, but in fact, the probability of wildfire occurrence fluctuates around a certain value, so it is difficult to accurately assess the probability of wildfire occurrence [12]. Based on this, firstly, the human and environmental errors are considered in the wildfire fault. Then, the triangular fuzzy probability, error limits and importance degree of the events are obtained. Finally, the causes of probability fluctuation and proper measures are raised, this model is applied to the wildfire fault in Zhaotong City, Yunnan Province, China.

2. F-FTA theory

2.1. Explanation of triangular fuzzy theory

In Figure 1, where $m$ is the kernel of $\tilde{A}$, $u+l$ is the blindness of $\tilde{A}$, $a_{\tilde{A}}(x)$ is the function expression of the triangular fuzzy function, $\tilde{A}$ has 3 fuzzy numbers $l$, $m$ and $u$ denoted by $\tilde{A}(l,m,u)$, and the function calculation method is:

$$a_{\tilde{A}}(x)=\begin{cases} 
\frac{(x-(m-l))}{l} & (m-l) \leq x < m \\
\frac{(m+u-x)}{u} & m \leq x \leq (m+u) \\
0 & \text{other}
\end{cases}$$

(1)

2.2. $\tilde{A}(l,m,u)$ algorithm

Let's assume that $\tilde{a}_1$ is denoted as $(l_1,m_1,u_1)$ and $\tilde{a}_2$ is denoted as $(l_2,m_2,u_2)$, its algorithm can be expressed as (2):
Where $C$ is normal number.

2.3. Drawing fault tree

Fault Tree Analysis (FTA) is a safety analysis and evaluation method for safety system engineering. Which finds out the causes of accidents or faults [13] and puts forward improvement measures to improve the safety of the system. According to a certain logic analysis, we use qualitative or quantitative methods, find the basic events of the fault tree, and draw the fault tree of Figure 2.

![Figure 2. Wildfire fault tree.](image)

2.4. Triangular fuzzy processing of basic events

Generally, we assume that the event obeys normal probability distribution, and the probability of distribution interval $[m - 3\sigma, m + 3\sigma]$ is exactly 99.7%, then we will consider that $3\sigma$ is the fluctuation limit of the events, after the triangular fuzzy probability of the events through simple formula operation can be obtained.

On the one hand the exact probability of a basic event with a certain probability is not fixed which continues to fluctuate around a certain value, so it is necessary to fuzz the accurate basic event and convert it into a triangular fuzzy probability. But one the other hand the basic events without accurate probability need to be fuzzed, the estimated value of the basic event is given according to the expert
scoring method. In addition, the average value is $v$ and the standard deviation is $\sigma$, the fuzzy probability is obtained by a simple operation.

### Table 1. Wildfire fault tree symbol and meaning.

| Symbol | Meaning | Symbol | Meaning |
|--------|---------|--------|---------|
| $T_1$  | Wildfire | $X_{12}$ | Fire isolation belt |
| $M_1$  | Combustible | $X_{13}$ | Train leak |
| $M_2$  | Suitable weather | $X_{14}$ | Friction fire |
| $M_3$  | Fire source | $X_{15}$ | Locomotive fire |
| $M_4$  | Litter | $X_{16}$ | Smoking in the wild |
| $M_5$  | Productive ignition source | $X_{17}$ | Heating and cooking |
| $M_6$  | Non-productive ignition source | $X_{18}$ | Sacrificial fire |
| $M_7$  | Not processed in time | $X_{19}$ | Driving the beasts |
| $X_1$  | Not processed | $X_{20}$ | Children playing with fire |
| $X_2$  | Low relative humidity | $X_{21}$ | Dementia playing with fire |
| $X_3$  | High wind speed | $X_{22}$ | Home fire |
| $X_4$  | Suitable temperature | $X_{23}$ | Deliberate arson |
| $X_5$  | Good sunshine | $X_{24}$ | Lightning strike |
| $X_6$  | Less precipitation | $X_{25}$ | Funeral fire |
| $X_7$  | Missing | $X_{26}$ | Self-ignition |
| $X_8$  | Burning charcoal | $X_{27}$ | Leakage |
| $X_9$  | Burning woodland | $X_{28}$ | Other ignition source |
| $X_{10}$ | Burning pasture | $X_{29}$ | Irrational arrangement |
| $X_{11}$ | Kiln | $X_{30}$ | A lot of fallen leaves |

### 2.5. The principle of triangular fuzzy probability’ calculating

The Principle of fuzzy “and gate” events’ calculating:

$$\tilde{q}_{an} = \tilde{q}_1 \otimes \tilde{q}_2 \otimes \tilde{q}_3 \otimes \cdots \otimes \tilde{q}_s = (l_{an}, m_{an}, u_{an})$$

(3)

The Principle of fuzzy “or gate” events’ calculating:

$$\tilde{q}_{or} = (l_{or}, m_{or}, u_{or}) = ((I - (I - \prod_{k=1}^{n} l_k)), (I - (I - \prod_{k=1}^{n} m_k)), (I - (I - \prod_{k=1}^{n} u_k)))$$

(4)

### 2.6. The importance’degree of basic events

$$T = S_i - S$$

(5)

Where $T$ is the fuzzy importance’ degree, $S_i$ is the median of the triangular fuzzy probability distribution of the basic event, $S$ is the median of the triangular fuzzy probability distribution of the top event.

The greater the fuzzy importance’ degree $T$ is, the greater the corresponding basic events on the top events’ impact is. Therefore we should give priority to the important one when we take measures to improve the security of the system.
3. Case application

3.1. Introduction to geographical & environment

Taking Zhaotong City, Yunnan Province, China as an example, Zhaotong City is located in the northeastern part of Yunnan Province at the junction of Sichuan, Guizhou and Yunnan provinces, which is seated in the hinterland of Wumeng Mountain and has an average elevation of 1,685 meters. Furthermore, the City whose forest coverage rate is 35% is rich in natural resources ranging from the southern subtropical to the northern temperate plants, including 12 nature reserves and 3 national nature reserves. In fact there are 31 ethnic minorities accounting for 10.67% of ethnic minorities such as Hui, Yi and Bai in Zhaotong City.

![Geographical Situation of Zhaotong City](image)

Figure 3. Zhaotong city’ geographical & environment.

3.2. Fault tree establishment

| Symbol | Score | Symbol | Score |
|--------|-------|--------|-------|
| $X_1$  | 0.041 | $X_{16}$ | 0.056 |
| $X_2$  | 0.012 | $X_{17}$ | 0.016 |
| $X_3$  | 0.052 | $X_{18}$ | 0.085 |
| $X_4$  | 0.026 | $X_{19}$ | 0.035 |
| $X_5$  | 0.019 | $X_{20}$ | 0.058 |
| $X_6$  | 0.052 | $X_{21}$ | 0.016 |
| $X_7$  | 0.015 | $X_{22}$ | 0.016 |
| $X_8$  | 0.089 | $X_{23}$ | 0.032 |
| $X_9$  | 0.056 | $X_{24}$ | 0.016 |
| $X_{10}$ | 0.065 | $X_{25}$ | 0.006 |
| $X_{11}$ | 0.021 | $X_{26}$ | 0.003 |
| $X_{12}$ | 0.015 | $X_{27}$ | 0.031 |
| $X_{13}$ | 0.012 | $X_{28}$ | 0.023 |
| $X_{14}$ | 0.012 | $X_{29}$ | 0.023 |
| $X_{15}$ | 0.006 | $X_{30}$ | 0.012 |
According to the table 3, the triangular fuzzy probability of the top event is (0.0024, 0.020, 0.071). In other words the calculation results show that the probability of wildfire is 0.020, the upper limit probability is 0.071, and the lower limit probability is 0.0024.

There are many ethnic minorities in Zhaotong City with ethnic activities, so the possibility of exposure to fire is greater, such as the Torch Festival of the Yi and Bai nationalities. At the same time, the planting time is more scattered; other incidents that cause wildfires are coincidental. Therefore, the probability of wildfires’ occurrence fluctuates greatly, and it is difficult for relevant personnel to manage forests. So it is necessary to implement targeted measures according to the seasons and regions.

**Table 3. Triangular fuzzy probability table of wildfire fault in Zhaotong city.**

| Symbol | Probability | Symbol | Probability |
|--------|-------------|--------|-------------|
|        | l           | u      | m           | l           | u      | m           |
| $X_1$  | 0.023       | 0.045  | 0.068       | $X_{16}$    | 0.009  | 0.032       | 0.056       |
| $X_2$  | 0.003       | 0.015  | 0.027       | $X_{17}$    | 0.010  | 0.021       | 0.033       |
| $X_3$  | 0.030       | 0.056  | 0.082       | $X_{18}$    | 0.051  | 0.083       | 0.115       |
| $X_4$  | 0.016       | 0.034  | 0.053       | $X_{19}$    | 0.026  | 0.037       | 0.048       |
| $X_5$  | 0.013       | 0.021  | 0.029       | $X_{20}$    | 0.034  | 0.057       | 0.079       |
| $X_6$  | 0.015       | 0.051  | 0.086       | $X_{21}$    | 0.007  | 0.018       | 0.029       |
| $X_7$  | 0.004       | 0.017  | 0.030       | $X_{22}$    | 0.009  | 0.023       | 0.036       |
| $X_8$  | 0.047       | 0.081  | 0.115       | $X_{23}$    | 0.009  | 0.025       | 0.041       |
| $X_9$  | 0.035       | 0.072  | 0.110       | $X_{24}$    | 0.008  | 0.027       | 0.047       |
| $X_{10}$ | 0.045    | 0.066  | 0.087       | $X_{25}$    | 0.0036 | 0.0063      | 0.010       |
| $X_{11}$ | 0.011    | 0.025  | 0.040       | $X_{26}$    | 0.0001 | 0.003       | 0.005       |
| $X_{12}$ | 0.006    | 0.016  | 0.026       | $X_{27}$    | 0.022  | 0.029       | 0.036       |
| $X_{13}$ | 0.002    | 0.009  | 0.017       | $X_{28}$    | 0.012  | 0.032       | 0.053       |
| $X_{14}$ | 0.002    | 0.007  | 0.012       | $X_{29}$    | 0.039  | 0.066       | 0.093       |
| $X_{15}$ | 0.003    | 0.006  | 0.010       | $X_{30}$    | 0.002  | 0.017       | 0.032       |

**Figure 4. Basic event triangular fuzzy probability & error distribution.**

As shown in Figure 3, the six basic events with the highest degree of fuzzy importance are: Sacrificial fire ($X_{18}$), Burning Charcoal ($X_8$), Burning woodland ($X_9$), Smoking in the wild ($X_{16}$),
Burning pasture ($X_{10}$), Children playing with fire ($X_{20}$). There are many ethnic minorities in Zhaotong City, Yunnan Province accompanied many sacrificial activities, which are easy to cause wildfires. Therefore, the publicity of fire safety is intensified, and people are encouraged to use fire in areas far away from inflammable materials; in the Qingming Festival and other important festivals, the department needs to increase publicity and patrols. At the same time, Yunnan Province has many mountainous areas with backward transportation and backward economy. So it is easy for formers who relying mainly on agriculture and heavily on land to expand the planting area by burning forests. In a word, it is for fire prevention more difficult because incidents that cause wildfires are more frequent and occasional, publicity is carried out by increasing warning slogans, propaganda banners, and attaching importance to family education.

4. Conclusion
The triangular fuzzy probability of the wildfire fault is (0.0024, 0.021, 0.071), so the prevention and control is more difficult because the width of the upper and lower limits is larger. Therefore, it is necessary to establish a sound regulation system and increase the number of the site that will develop and implement individualized measures in a targeted manner to provide guidance for wildfire prevention.

The six basic events with the highest degree of fuzzy importance are: Sacrificial fire ($X_{18}$), Burning charcoal ($X_8$), Burning woodland ($X_9$), Smoking in the wild ($X_{16}$), Burning pasture ($X_{10}$), Children playing with fire ($X_{20}$). Therefore, the forestry department needs to increase the propaganda of firing safely during the Ching Ming Festival and the holidays of ethnic minority sacrifices, arranging full-time personnel to increase patrols. Furthermore relevant government departments need to increase support for mountain residents, improve the people's living standards, and prompt people to abandon the habit of setting off firecrackers, throwing cigarette butts casually and other bad habits.

Acknowledgments
This work is financially supported by the National Key Research and Development Project of China [grant numbers 2016YFC0802500]; National Natural Science Foundation of China (NSFC) [grant numbers 71790613].

References
[1] Choobineh, M., B. Ansari and S. Mohagheghi, Vulnerability assessment of the power grid against progressing wildfires. FIRE SAFETY JOURNAL, 2015. 73: p. 20-28.
[2] Franca, G.B., et al., A Fire-Risk-Breakdown System for Electrical Power Lines in the North of Brazil. JOURNAL OF APPLIED METEOROLOGY AND CLIMATOLOGY, 2014. 53(4): p. 813-823.
[3] Stambaugh, M.C., et al., Future southcentral US wildfire probability due to climate change. CLIMATIC CHANGE, 2018. 147(3-4): p. 617-631.
[4] Vacchiano, G., et al., Modeling anthropogenic and natural fire ignitions in an inner-alpine valley. NATURAL HAZARDS AND EARTH SYSTEM SCIENCES, 2018. 18(3): p. 935-948.
[5] Tane, Z., et al., Evaluating Endmember and Band Selection Techniques for Multiple Endmember Spectral Mixture Analysis using Post-Fire Imaging Spectroscopy. REMOTE SENSING, 2018. 10(3893).
[6] Rui, X., et al., Forest fire spread simulation algorithm based on cellular automata. NATURAL HAZARDS, 2018. 91(1): p. 309-319.
[7] Fang, L., et al., Predicting Potential Fire Severity Using Vegetation, Topography and Surface Moisture Availability in a Eurasian Boreal Forest Landscape. FORESTS, 2018. 9(1303).
[8] Xu, K., et al., Risk assessment for wildfire occurrence in high-voltage power line corridors by using remote-sensing techniques: a case study in Hubei Province, China. INTERNATIONAL JOURNAL OF REMOTE SENSING, 2016. 37(20): p. 4818-4837.
[9] Fang, L., et al., Predicting Potential Fire Severity Using Vegetation, Topography and Surface
Moisture Availability in a Eurasian Boreal Forest Landscape. FORESTS, 2018. 9(1303).

[10] Reilly, M.J., et al., Cumulative effects of wildfires on forest dynamics in the eastern Cascade Mountains, USA. ECOLOGICAL APPLICATIONS, 2018. 28(2): p. 291-308.

[11] Lu, J., et al., Optimal Allocation of Fire Extinguishing Equipment for a Power Grid Under Widespread Fire Disasters. IEEE ACCESS, 2018. 6.

[12] Zarei, E., et al., A hybrid model for human factor analysis in process accidents: FBN-HFACS. Journal of Loss Prevention in the Process Industries, 2019. 57: p. 142-155.

[13] JIANG, G., et al., A new approach to fuzzy dynamic fault tree analysis using the weakest n-dimensional t-norm arithmetic. Chinese Journal of Aeronautics, 2018. 31(7): p. 1506-1514.