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Application of fault tree approach for the causation mechanism of urban haze in Beijing—Considering the risk events related with exhausts of coal combustion

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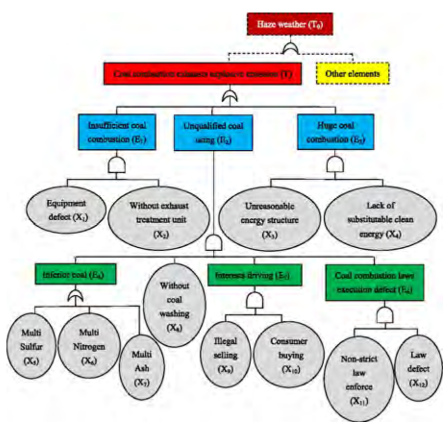
HIGHLIGHTS

- Fault tree approach was employed for the causation mechanism analysis of urban haze in Beijing—considering the risk events related with the exhausts of coal combustion
- Risk events of the causation system of urban haze connecting with coal combustion exhausts were defined and elaborated.
- Successful quantitative analysis of the risk events was completed in the causation system of urban haze connecting with the exhausts of coal combustion.

GRAPHICAL ABSTRACT



Fault tree approach was employed as an effective and simple tool for the causation mechanism analysis and risk management of urban haze in Beijing for the first time—considering the risk events related with the exhausts of coal combustion.

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ABSTRACT

Haze weather has become a serious environmental pollution problem which occurs in many Chinese cities. One of the most critical factors for the formation of haze weather is the exhausts of coal combustion, thus it is meaningful to figure out the causation mechanism between urban haze and the exhausts of coal combustion. Based on above considerations, the fault tree analysis (FAT) approach was employed for the causation mechanism of urban haze in Beijing by considering the risk events related with the exhausts of coal combustion for the first time. Using this approach, firstly the fault tree of the urban haze causation system connecting with coal combustion exhausts was established; consequently the risk events were discussed and identified; then, the minimal cut sets were successfully determined using Boolean algebra; finally, the structure, probability and critical importance degree analysis of the risk events were completed for the qualitative and quantitative assessment. The study results proved that the FTA was an effective and simple tool for the causation mechanism analysis and risk management of urban haze in China.

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1. Introduction

After the London haze incidents in 1952, the 2013 severe haze event in China astonished the world again. Haze weather has become a severe environmental pollution problem in many Chinese cities. $PM_{2.5}$ (particulate matters with aerodynamic diameter ≤ 2.5 μm) contributing the most to the haze pollution that will affect air quality, human health and regional climate (Zhang et al., 2013). A statement of "Reinforcing the haze treatment, to eliminate the lung hazard and heart afraid for Chinese citizen" was proposed by the China Premier Keqiang Li in the executive meetings of China's State Council in February 2014, which indicated the determination of China government in the haze pollution control. Recently, some researchers had paid attention to the formation mechanism and environmental impact of urban haze in China (Gao et al., 2015; Tie et al., 2015; Zhang et al., 2015; Zhang et al., 2014). Huang et al. (2014a,b) combined a comprehensive set of novel and state-of-the-art offline analytical approaches and statistical techniques to investigate the chemical nature and sources of particulate matter at urban locations in Beijing, Shanghai, Guangzhou and Xi'an during January 2013, their analysis results showed that the severe haze pollution event was driven to a large extent by secondary aerosol formation, and the fossil fuel combustion and biomass burning is likely to be important for controlling China's $PM_{2.5}$ levels. Yang et al. (2015) investigated the formation and evolution mechanism of the regional haze in Beijing by using the atmospheric environmental monitoring data from meteorology perspective, the analysis results of the high variability in Cl^- and K^+ indicated that large quantities of coal combustion and biomass burning occurred during the haze. Based on the above literatures, the exhausts of coal combustion can be considered as one of the critical factors leading to haze pollution. The process control and environmental risk analysis for coal combustion were also discussed (Minchener, 2013; Xie et al., 2010). Qian and coworkers made great progress on the techno-economic analysis, energy efficiency and environmental assessment for coal to olefins or gasification process recently (Li et al., 2015; Man et al., 2014a; Man et al., 2014b; Qian et al., 2009; Xiang et al., 2014; Yang et al., 2012; Yang et al., 2013). However, most of the haze formation researches mentioned above made the achievement based on the professional perspectives from meteorology, pollutants composition and aerosol formation mechanism. For providing valuable information for the public to recognize the causation mechanism of urban haze more easily by understanding the risk events related with the exhausts of coal combustion, from the perspective of systematic methodology, the fault tree analysis (FTA) approach was employed to provide a simple and effective tool for the causation mechanism analysis. It may also be useful for the government to adopt scientific approach and improve relevant policy to intervene and eliminate the occurrence of urban haze in China.

Fault tree analysis (FTA) is a deductive, top-down method aimed at analyzing the effects of risk factors on a complex system (Bedford & Cooke, 2001), which had been applied in numerous fields such as power distribution systems, water supply systems, fuel cell degradation and biogas systems (Abdul et al., 2013; Cheng et al., 2014; Lindhe et al., 2012; Placca & Kouta, 2011; Volkanovski et al., 2009). Compared to other methods, it has a readable and understandable logic background structure and would thus be more easily accepted. In this study, FAT was employed to qualitatively and quantitatively analyze the causation mechanism of urban haze related to the exhausts of coal combustion for Beijing city for the first time. By establishing the fault tree of "Haze weather—coal combustion exhausts explosive emission", the risk events were discussed and identified. This study may provide a scientific and effective tool for the causation mechanism analysis and risk management of haze pollution in China.

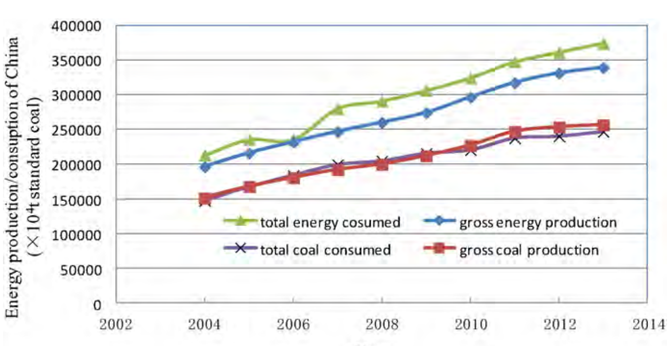

Fig. 1. Energy production/consumed trend in China.

2. Coal combustion scenario in Beijing

To build the fault tree properly for the causation mechanism analysis between urban haze and the exhausts of coal combustion in Beijing, some relevant survey about the coal combustion scenario in Beijing should be done to prefer the qualitative or quantitative analysis.

(1) According to 2014 China Energy Statistical Yearbook (National Bureau of Statistics of China, 2015), the national energy production/consumption of China during 2004–2013 is concluded and shown as Fig. 1,which indicated that China still have to import energy from other countries, because the energy production was less than the energy consumption annually. Coal still was the most important energy of China, which taken 75.6% of the gross energy production and 66% of the total energy consumed as the data shown in 2013. According to 2014 Beijing Statistical Yearbook (National Bureau of Statistics of China, 2015), the energy production/consumption trend is also concluded and shown as Fig. 2, which indicated that coal still was the key energy source in Beijing and taken 22.53% of the total energy consumed in Beijing as the data shown in 2012. The coal consumption still up to about 2000×10^4 t each year, although the Beijing government try to lower down the coal consumption in recent years.

(2) According to the 2013 Environmental Statistics Annual Report from Beijing Municipal Environmental Protection Bureau (Beijing Municipal Environmental Protection Bureau, 2014), the atmospheric environment pollutants were mainly focusing on the emission of SO_2, NO_x, and dust. Most of the pollution emissions were closely connected with the coal combustion, as shown in Table 1.

(3) According to the statistical data from Beijing Municipal Environmental Protection Bureau (Beijing Municipal Environmental Protection Bureau, 2015), coal combustion taken 22.4% in the local pollutant sources of $PM_{2.5}$ in Beijing, as show in Fig. 3.

Coal is such an important energy sources in China and Beijing, coal combustion exhausts also can be regard as the critical contributor to $PM_{2.5}$ which is believed to be the most important air pollutants causing haze weather in China. Thus it is meaningful to figure out the causation mechanism between urban haze and coal combustion. In this work, the FAT method is introduced to solve the causation mechanism analysis problem for the causation system of urban haze connecting with the exhausts of coal combustion in Beijing.

3. Fault tree establishing and analysis

3.1. The procedure of fault tree analysis

FTA is a systematic method for analyzing the cause of risks by adopting a deductive method qualitatively and quantitatively, and the Fault Tree (FT) is a graphic expression to show how an undesirable event can occur in different ways and systematically identify the probable sequence of events (Hyun et al., 2015). The occurrence of the top event can be quantitatively estimated based on the probability of each risk's occurring. However, it is difficult to get the precise occurrence probability of the risk events, which always shows uncertain property in comprehensive chemical systems (Huang et al., 2014b; Huang et al., 2011; Huang et al., 2014a). The procedure of the FAT method is shown

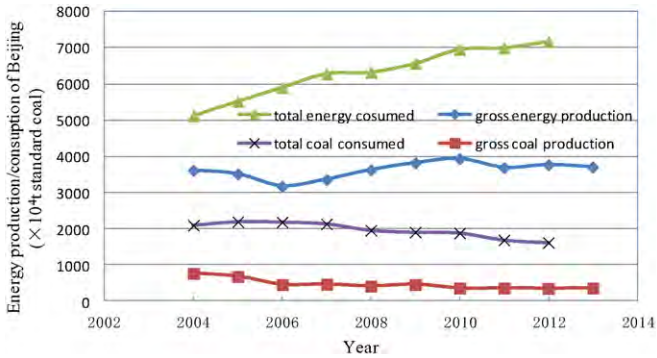

Fig. 2. Energy production/consumed trend of Beijing.

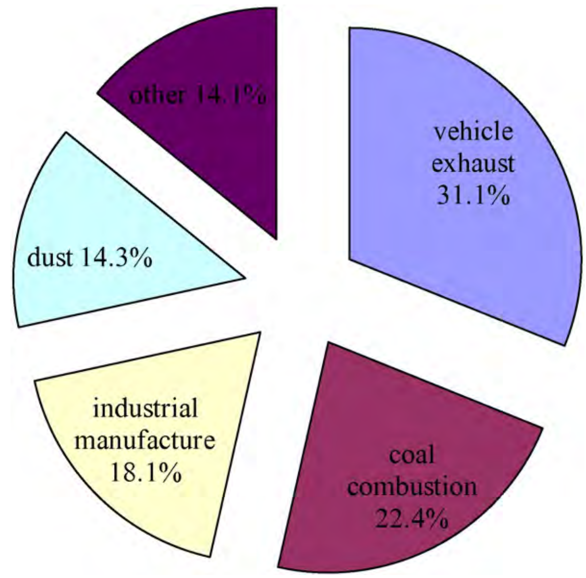

Fig. 3. Local pollutant sources of $PM_{2.5}$ in Beijing.

as Fig. 4. The method can explain how risk factors can be combined to cause a risk in the relevant primary system. So proper measures can be taken to interdict the development of the top event (coal combustion exhausts explosive emission) and prevent the final undesirable event (haze weather).

3.2. Building fault tree

The most undesirable specific risk category is always defined as the top event in the primary system of the fault tree. Except the meteorological condition, the pollution such as coal combustion exhausts, vehicle exhausts, industrial processes wastes, and dust are key factors in the formulation of haze weather. Although coal combustion exhausts emission is not the only reason leading to haze pollution, however, when other conditions is sufficient, the coal combustion exhausts explosive emission can make the haze weather happen. So, in this work, the "coal combustion exhausts explosive emission" is identified as the undesirable top event for the causation system of urban haze connecting with the exhausts of coal combustion in Beijing. The direct and potential events leading to the "coal combustion exhausts explosive emission" are figured out by analyzing the theoretical relation between the risk categories (top events), the risks (gates or sub-gates) and the risk factors (events) based on AND and OR logic. This work may provide an effective new tool/strategy for the causation mechanism analysis and environmental risk management of haze pollution in China.

After the technical information investigation and the risk factors survey in the researches mentioned above and some other references (Saikia et al., 2015; Tao et al., 2015; Xu et al., 2015), the elements selected in the fault tree are mainly based on the "Action Plan on Prevention and Control of Air Pollution" (China's State Council, 2013) and the report of the "Coal Use Contribution to China's Air Pollution" (NRDC, 2014). It had been revealed that coal combustion contributed over 50% to the air pollution in China, and the concentration of $PM_{2.5}$ increases if the coal consumption increases which was up to the coal-based energy structure in China (NRDC, 2014). Unqualified coal using can enlarge the environmental pollution especially those inferior coal containing high Sulfur, Nitrogen and Ash were burning without pretreatment, so coal-washing technology and other helpful combustion technologies were recommend to reduce the environmental burden (Xu et al., 2015). The efficiency of the coal combustion in industrial boiler and household heating should be enhanced to decrease the air pollution and energy waste, the human factors such as coal-fired law, interests driving also are key factors cannot be ignored (China's State Council, 2013). According to the above analyses, all the elements selected in the fault tree are listed in Table 2 by using the deductive method (FTA). The Huge coal combustion, insufficient coal combustion, and unqualified coal using are identified as sub-events of the top event (coal combustion exhausts explosive emission) after the deducing and analysis. The whole fault tree system built is shown as Fig. 5.

In the fault tree, the rectangle represents the top event or intermediate event that results from the logical combination of risk factors (basic events) through the input of the logic gate. The circle denotes a basic fault event or the failure of an elementary part. AND gate, denotes that an output fault event occurs only if all of the input fault events occur. OR gate, denotes that an output fault event occurs if one or more of the input fault events occur.

Table 1
Pollutant emission survey of atmospheric environment in Beijing in 2013. (Beijing Municipal Bureau of Statistics, 2015).

Atmospheric pollutant	Emission in 2013 (t)
SO_2	87,042
Including:industry SO_2	52,041
City living SO_2	34,967
Centralization treatment facility SO_2	34
NO_x	166,329
Including:industry NO_x	75,927
City living NO_x	13,638
Vehicle NO_x	76,472
Centralization treatment facility NO_x	292
Dust	59,286
Including:industry dust	27,182
City living dust	28,258
Vehicle dust	3806
Centralization treatment facility dust	40

3.3. Qualitative analysis

A fault tree is developed using logic gates such as OR and AND that relate logically various basic fault events to the undesirable or the top event. According to the fault tree analysis procedure shown in Fig. 4, to carry out the qualitative and quantitative analysis for the "Haze weather—Coal combustion exhausts explosive emission" fault tree, the minimal cut sets should be obtained to simplify the fault tree using Boolean algebra firstly.

3.3.1. Obtaining the minimum cut sets

A cut set may be described as a collection of basic events that will cause the top event to occur. Furthermore, a cut set is said to be minimal if it cannot be further minimized or reduced but it can still ensure the occurrence of the top event. By using the Boolean algebra, the "Haze weather—Coal combustion exhausts explosive emission" fault tree can

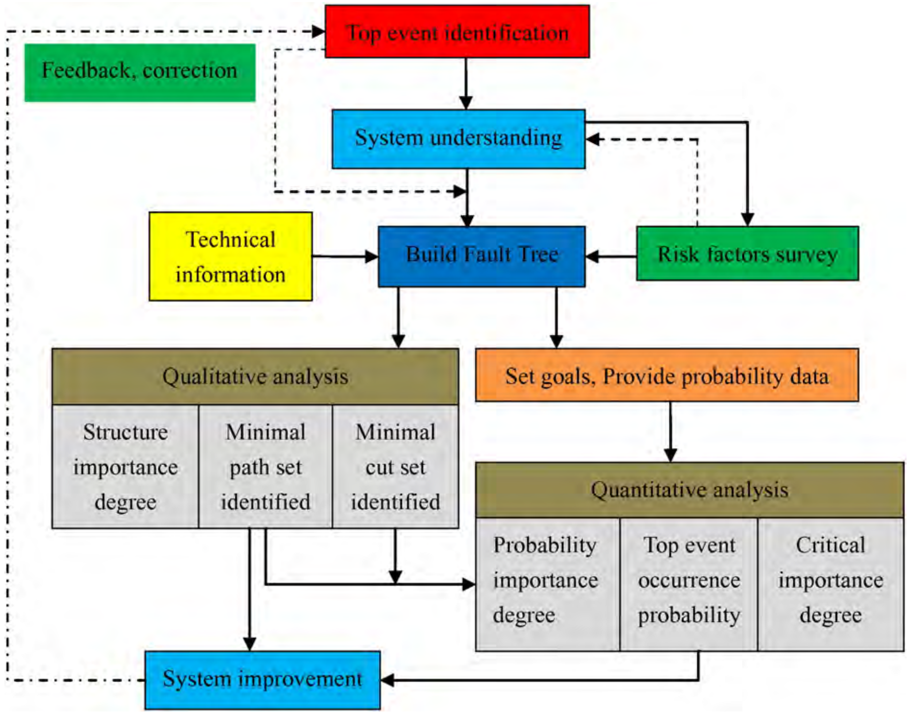

Fig. 4. The procedure of Fault Tree Analysis.

be simplified as:

$$\begin{aligned} T &= E_1 + E_2 + E_3 \\ &= X_1X_2 + E_4E_5E_6X_8 + X_3X_4 \\ &= X_1X_2 + (X_5 + X_6 + X_7) * (X_9X_{10}) * (X_{11}X_{12}) * X_8 + X_3X_4 \\ &= X_1X_2 + X_5X_8X_9X_{10}X_{11}X_{12} + X_6X_8X_9X_{10}X_{11}X_{12} \\ &\quad + X_7X_8X_9X_{10}X_{11}X_{12} + X_3X_4 \end{aligned}$$

After the simplification, five minimum cut sets are obtained, as shown below.

$$K_1 = \{X_1, X_2\}; K_2 = \{X_5, X_8, X_9, X_{10}, X_{11}, X_{12}\}; K_3 = \{X_6, X_8, X_9, X_{10}, X_{11}, X_{12}\}; K_4 = \{X_7, X_8, X_9, X_{10}, X_{11}, X_{12}\}; K_5 = \{X_3, X_4\}.$$

So the equivalent tree of the "Haze weather—Coal combustion exhausts explosive emission" fault tree can be demonstrated as Fig. 6 after the simplification. In the equivalent tree, five combinations show the potential to make the top event of "Coal combustion exhausts explosive emission" occur. As the minimum cut set K_5 shows, when both of the basic events of X_3 (Unreasonable energy structure) and X_4 (Lack of substitutable clean energy) happen together, the top event of "Coal combustion exhausts explosive emission" may occur and lead to the occurrence of the haze weather too.

Table 2
Risk factors and probability values of the fault tree.

Risk factors	Probability values
Insufficient coal combustion (E_1)	
Equipment defect (X_1)	0.3
Without exhaust treatment unit (X_2)	0.3
Huge coal combustion (E_3)	
Unreasonable energy structure (X_3)	0.4
Lack of substitutable clean energy (X_4)	0.4
Unqualified coal using (E_2)	
Inferior coal (E_4)	
Multi Sulfur (X_5)	0.3
Multi Nitrogen (X_6)	0.3
Multi Ash (X_7)	0.3
Without coal washing (X_8)	0.3
Interests driving (E_5)	
Illegal selling (X_9)	0.15
Consumer buying (X_{10})	0.15
Coal combustion laws execution defect (E_6)	
Non-strict law enforce (X_{11})	0.1
Law defect (X_{12})	0.3

3.3.2. Structure importance degree analysis

Structure importance degree analysis is a qualitative method to assess the effect of the basic events to the top event only based on the fault tree structure, while without considering the probability of occurrence of the basic events. It is useful when the probability data of the basic events cannot be attained. The approximate discriminant for the structure importance degree analysis can be shown as:

$$\mathbf{I}(i) = \sum_{X_i \in K_r} \frac{1}{2^{n_i - 1}} \tag{1}$$

where $\mathbf{I}(i)$ denotes the structure degree coefficient of the basic event X_i, for i = 1,2,…,12; n_i denotes the number of the basic events in the minimum cut set including the basic event X_i; K_r denotes the number of the minimum cut sets including the basic event X_i. All the structure importance degree coefficient of the basic events based on Eq. (1) is demonstrated as follows:

$$I(1) = 0.5; I(2) = 0.5; I(3) = 0.5; I(4) = 0.5; I(5) = 0.03125; I(6) = 0.03125;$$

$$I(7) = 0.03125; I(8) = 0.09375; I(9) = 0.09375; I(10) = 0.09375;$$

$$I(11) = 0.09375; I(12) = 0.09375.$$

So the structure importance degree of the basic events is ordered as:

$$I(1) = I(2) = I(3) = I(4) > I(8) = I(9) = I(10) = I(11) = I(12) > I(5) = I(6) = I(7).$$

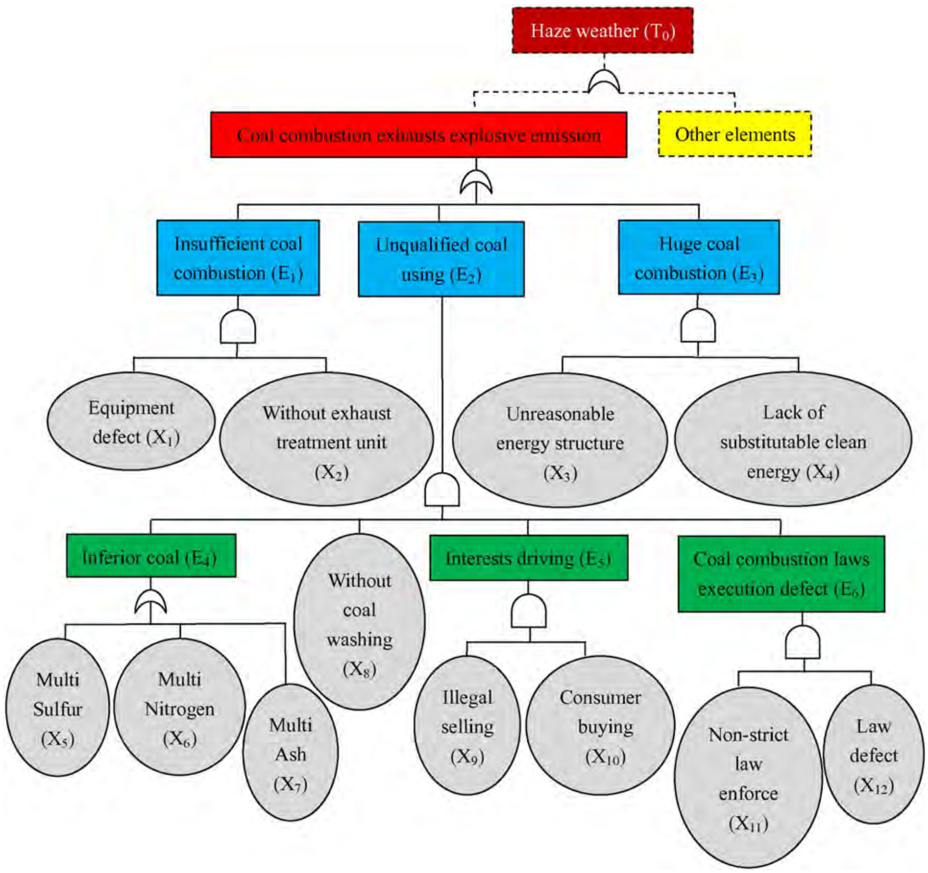

Fig. 5. The "Haze weather—Coal combustion exhausts explosive emission" fault tree.

According to the qualitative analysis results of the "Haze weather—Coal combustion exhausts explosive emission" fault tree, it can come to a conclusion that the Unreasonable energy structure (X_3), Lack of substitutable clean energy (X_4), Equipment defect (X_1), and Without exhaust treatment unit (X_2) show more important effect to the top event. The basic events of X_3 and X_4 can cause the Huge coal combustion (E_3) occur. The basic events of X_1 and X_2 can cause the Insufficient coal combustion (E_1) occur and lead to more exhausts emission. Those important risk factors should be pay more attention to prevent the "Haze weather—Coal combustion exhausts explosive emission".

3.4. Quantitative analysis

After obtaining minimal cut sets and equivalent tree of the "Haze weather—Coal combustion exhausts explosive emission" fault tree, one can proceed to determine the probability of occurrence of the top event. This probability can be obtained by firstly estimating the occurrence probability of the basic risk events which are always based on the empirical data or the expert's suggestion. The basic risk events of the "Haze weather—Coal combustion exhausts explosive emission" fault tree shown in Fig. 5 are dependent with each other. Using the equivalent tree shown in Fig. 6, the occurrence probability of the output events based on OR gate can be given by

$$P(T) = 1-\prod_{i=1}^{m}(1-q_{K_i}) \quad (2)$$

where q_{Ki} is the occurrence probability of input event K_i; for $i = 1, 2, 3, \ldots, m$.

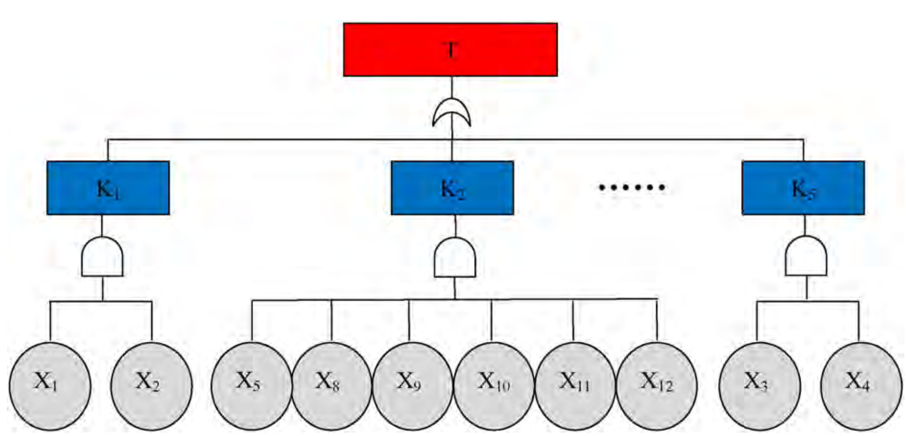

Fig. 6. The equivalent tree.

The occurrence probability of the output events K_i based on AND gate can be given by

$$P(K_i) = \prod_{i=1}^{n} q_{Xi} \tag{3}$$

where q_{Xi} is the occurrence probability of input event X_i; for i = 1, 2, 3,…, n.

The difficulty of the quantitative analysis is to estimate the occurrence probability of the basic events precisely. According to the survey of the coal combustion scenario in Beijing and some other relevant technical information, all of risk factors and the probability values of the basic risk events are listed in Table 2, which are mostly based on the expert's suggestion and the empirical data from experience.

So the probability of occurrence of the top event “Coal combustion exhausts explosive emission” is given as.

$$\begin{aligned} P(T) &= 1-\prod_{i=1}^{5}(1-P_{K_i}) \\ &= 1-(1-)(1-)(1-)(1-)(1-) \\ &= 1-(1-q_1q_2)(1-q_3q_4)(1-q_5q_8q_9q_{10}q_{11}q_{12}) \\ &\quad (1-q_6q_8q_9q_{10}q_{11}q_{12}) \\ &\quad *(1-q_7q_8q_9q_{10}q_{11}q_{12}) \\ &= 0.2357. \end{aligned}$$

3.4.1. Probability importance degree analysis

The structure importance degree analysis only rely on the fault tree structure, while without considering the effect of the occurrence probability of the basic events to the top event. The probability importance degree analysis can be employed to figure out how the occurrence probability change of the basic event will affect the occurrence probability change of the top event, which is demonstrated as following:

$$I_g(i) = \frac{\partial P(T)}{\partial q_i} \tag{4}$$

where $I_g(i)$ denotes the probability importance degree of the basic event X_i, P(T) is the probability function of the top event, q_i denotes the probability variable of the basic event X_i. According to Eq. (4), all the probability importance degree coefficients can be calculated and listed as follows.

$$\begin{aligned} I_g\,(1) &= q_2(1-q_3q_4)(1-q_5q_8q_9q_{10}q_{11}q_{12})(1-q_6q_8q_9q_{10}q_{11}q_{12}) \\ &\quad \times(1-q_7q_8q_9q_{10}q_{11}q_{12}) \\ &= 0.252 \end{aligned}$$

$$\begin{aligned} I_g\,(2) &= 0.252; I_g\,(3) = 0.364; I_g\,(4) = 0.364; I_g\,(5) \\ &= 1.548 \times 10^{-4}; I_g\,(6) = 1.548 \times 10^{-4}; \end{aligned}$$

$$\begin{aligned} I_g\,(7) &= 1.548 \times 10^{-4}; I_g\,(8) = 4.6432 \times 10^{-4}; I_g\,(9) \\ &= 9.2864 \times 10^{-4}; I_g\,(10) = 9.2864 \times 10^{-4}; \end{aligned}$$

$$I_g\,(11) = 1.3929 \times 10^{-3}; I_g\,(12) = 4.6432 \times 10^{-4}.$$

So the probability importance degree of the basic events is ordered as following:

$$\begin{aligned} I_g\,(3) &= I_g\,(4) > I_g\,(1) = I_g\,(2) > I_g\,(11) > I_g\,(9) = I_g\,(10) > I_g\,(8) \\ &= I_g\,(12) > I_g\,(5) = I_g\,(6) = I_g\,(7). \end{aligned}$$

The probability importance degree analysis can be used to uncover which basic event's probability reducing can lower down the occurrence probability of the top event rapidly. According to the analysis results, it can come to a conclusion that the Unreasonable energy structure (X_3), Lack of substitutable clean energy (X_4), Equipment defect (X_1), and Without exhaust treatment unit (X_2) show more important effect to the top event. Those important risk factors should be pay more attention.

3.4.2. Critical importance degree analysis

As Eq. (4) shows, the probability importance degree coefficient of basic event X_i is determined by other event's probability. It did not reveal the probability effect of the basic event X_i itself to the top event directly. The critical importance degree analysis provide a more accurate assessment approach which is defined as the relative probability change ratio of the top event divided by the relative probability change ratio of the basic event X_i:

$$I_g^c(i) = \lim_{\Delta q_i \to 0} \frac{\Delta P(T) / P(T)}{\Delta q_i / q_i} = \frac{q_i}{P(T)} \cdot \lim_{\Delta q_i \to 0} \frac{\Delta P(T)}{\Delta q_i} = \frac{q_i}{P(T)} \cdot I_g(i) \tag{5}$$

where $I_g^c(i)$ is the critical importance degree coefficient of basic event X_i; $I_g(i)$ denotes the probability importance degree of the basic event X_i; P(T) is the probability of top event; q_i denotes the occurrence probability of the basic event X_i. According to Eq. (5), all the critical importance degree coefficients can be calculated and listed as following:

$$I_g^c(1) = \frac{q_1}{P(T)} \cdot I_g(1) = 0.3 * 0.252/0.2357 = 0.3207;$$

$$I_g^c(2) = 0.3207; I_g^c(3) = 0.6177; I_g^c(4) = 0.6177; I_g^c(5) = 1.9703 \times 10^{-4};$$

$$\begin{aligned} I_g^c(6) &= 1.9703 \times 10^{-4}; I_g^c(7) = 1.9703 \times 10^{-4}; I_g^c(8) \\ &= 5.910 \times 10^{-4}; I_g^c(9) = 5.910 \times 10^{-4}; \end{aligned}$$

$$I_g^c(10) = 5.910 \times 10^{-4}; I_g^c(11) = 5.910 \times 10^{-4}; I_g^c(12) = 5.910 \times 10^{-4}.$$

So the critical importance degree of the basic events is ordered as following:

$$\begin{aligned} I_g^c(3) &= I_g^c(4) > I_g^c(1) = I_g^c(2) > I_g^c(8) = I_g^c(9) = I_g^c(10) = I_g^c(11) \\ &= I_g^c(12) > I_g^c(5) = I_g^c(6) = I_g^c(7). \end{aligned}$$

According to the analysis results, it can also come to a conclusion that the Unreasonable energy structure (X_3), Lack of substitutable clean energy (X_4), Equipment defect (X_1), and Without exhaust treatment unit (X_2) show more important effect to the top event.

3.5. Analysis outcomes and prevention measures

According to the qualitative and quantitative analysis of the “Haze weather—Coal combustion exhausts explosive emission” fault tree, the primary causes and risk events can be figured out and the whole analysis results based on structure, probability, and critical importance degree are shown in Table 3. According to the analysis results, it can come to a conclusion finally that the Unreasonable energy structure (X_3), Lack of substitutable clean energy (X_4), Equipment defect (X_1), and Without exhaust treatment unit (X_2) show more important effect to the top event. Those important risk factors should be pay more attention and provided treatment measures to prevent the “Haze weather—Coal combustion exhausts explosive emission”. Besides that, Without coal washing (X_8), Illegal selling (X_9), Consumer buying (X_{10}), Non-strict law enforce (X_{11}), and Law defect (X_{12}) show secondary important effect.

Some prevention measures are discussed to perform the environment risk management based on the risk factors analysis results, which is listed in Table 4.

Table 3
Risk factors and the qualitative/quantitative analysis results.

Risk factors	Probability values	Structure importance degree coefficients	Probability importance degree coefficients	Critical importance degree coefficients
Haze weather—Coal combustion explosive emission (T)	0.2357			
Insufficient coal combustion (E_1)				
Equipment defect (X_1)	0.3	0.5	0.252	0.3207
Without exhaust treatment unit (X_2)	0.3	0.5	0.252	0.3207
Huge coal combustion (E_3)				
Unreasonable energy structure (X_3)	0.4	0.5	0.364	0.6177
Lack of substitutable clean energy (X_4)	0.4	0.5	0.364	0.6177
Unqualified coal using (E_2)				
Inferior coal (E_4)				
Multi Sulfur (X_5)	0.3	0.03125	1.548×10^{-4}	1.9703×10^{-4}
Multi Nitrogen (X_6)	0.3	0.03125	1.548×10^{-4}	1.9703×10^{-4}
Multi Ash (X_7)	0.3	0.03125	1.548×10^{-4}	1.9703×10^{-4}
Without coal washing (X_8)	0.3	0.09375	4.6432×10^{-4}	5.910×10^{-4}
Interests driving (E_5)				
Illegal selling (X_9)	0.15	0.09375	9.2864×10^{-4}	5.910×10^{-4}
Consumer buying (X_{10})	0.15	0.09375	9.2864×10^{-4}	5.910×10^{-4}
Coal combustion laws execution defect (E_6)				
Non-strict law enforce (X_{11})	0.1	0.09375	1.3929×10^{-3}	5.910×10^{-4}
Law defect (X_{12})	0.3	0.09375	4.6432×10^{-4}	5.910×10^{-4}

4. Conclusions

This study focused on the causation mechanism between urban haze and the exhausts of coal combustion for Beijing city by using the fault tree analysis (FAT) approach for the first time. Using this approach, firstly the fault tree of the urban haze causation system connecting with the exhausts of coal combustion was established; the risk events were consequently discussed and identified; then, the minimal cut sets were successfully determined using Boolean algebra; finally, the structure, probability and critical importance degree analysis of the risk events were also completed for the qualitative and quantitative assessment. The study results proved that the FTA was an effective and simple tool for the causation mechanism analysis and risk management of urban haze in China.

According to the qualitative and quantitative analysis results, it can come to a conclusion that the Unreasonable energy structure (X_3), Lack of substitutable clean energy (X_4), Equipment defect (X_1), and Without exhaust treatment unit (X_2) show more important effect to the top event. Those important risk factors should be pay more attention and provided treatment measures to prevent the "Haze weather—Coal combustion exhausts explosive emission". Besides that, Without coal washing (X_8), Illegal selling (X_9), Consumer buying (X_{10}), Non-strict law enforce (X_{11}), and Law defect (X_{12}) show secondary important effect. Although the risk events shown different effect to the top event, all the risk events need an overall consideration for the prevention and treatment of haze pollution.

It is hard to get the precise occurrence probability of the risk events once the quantitative analysis of FAT method was carried out, thus it did not complete the quantitative analysis for the application of FTA in most of the complex systems. In this study, the probability values of the risk events are mostly based on the expert's suggestion and the empirical data from experience. It would be interesting to find that if the occurrence probability of the top event "Coal combustion exhausts explosive emission" can be considered as the contribution weight of the coal combustion to the haze weather approximatively, the calculation result (23.57%) shows a high coincident with the contribution weight of coal combustion to the $PM_{2.5}$ (22.4%) in Beijing as shown in Fig. 3. This work may provide a practical and effective tool/strategy for risk management and environmental governance in the urban haze causation system related to the exhausts of coal combustion in China.

Table 4
Prevention measures for "Haze weather—Coal combustion exhausts explosive emission".

Risk factors	Prevention measures
Unreasonable energy structure (X_3), lack of substitutable clean energy (X_4)	Adjust energy structure, try to use cleaner energy, and exploit new energy.
Insufficient coal combustion (E_1), equipment defect (X_1), without exhaust treatment unit (X_2)	Improve coal combustion technical, let the coal burning sufficient, and install the exhaust treatment equipment during the coal combustion process.
Coal combustion laws execution defect (E_6), non-strict law enforce (X_{11}), law defect (X_{12})	Improve and complete the relevant law, set up the rigorous exhaust emission standard for coal combustion plant, reinforce the execution law.
Interests driving (E_5), illegal selling (X_9), consumer buying (X_{10})	Reinforce the public education and advertise the relevant rule.
Inferior coal (E_4)	Improve the coal quality; perform the coal washing, desulfuration and denitrification before coal combustion; try to use qualified coal such as anthracite and meager coal but not the brown coal.

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