Basic Event Probability Determination and Risk Assessment Based on Cause - Consequence Analysis Method

Baoquan Xin¹, ², *, Lu Wan², ¹, Jianliang Yu¹, ², b and Wenyi Dang², c

¹School of Chemical Engineering, Dalian University of Technology, Dalian 116024, China
²Sinopec Qingdao Research Institute of Safety Engineering, Qingdao 266101, China

*Corresponding author e-mail: xinbq123 @163.com, wanlu132@163.com,
yujianliang@dlut.edu.cn, dangwy.qday@sinopec.com

Abstract. Reasonable determination of the probability of occurrence of basic events is the basis of scientific risk assessment. The cause- consequence analysis method developed from the theory of system reliability is an effective method to determine the probability of basic events. Taking the motor overheating event as an example, based on the reliability theory of human and machine, from the perspective of "safety control system for the occurrence and development of motor overheating fire event", the "motor overheating safety control system" is determined as the target system. Through the investigation and analysis of the functional composition of the target system, the reliability block diagram of the target system is obtained. And the logical relationship of link events is determined. According to the reliability theory, the probability of each basic event is investigated and calculated. Finally, the risk assessment diagram of motor overheating is obtained. The results show that the equal risk line in logarithmic coordinate is a straight line. This line is the critical line of acceptable risk. This research solves the problems of the current cause effect analysis, such as the unclear choice of the target system, the confusion of the logical relationship between the link events and the unclear source of the basic data. The study of quantitative analysis details based on reliability theory improves the operability and application effect of cause consequence analysis method, which is helpful for its popularization and application.

1. Introduction
In the quantitative analysis of system security, the probability of occurrence of various events generally needs to be obtained based on system reliability theory and by analyzing the reliability of relevant equipment and people. These occurrence probabilities include the probability of an initiation event, the success or failure of a link event, and the occurrence probability of an event tree top event [1, 2]. Therefore, the reliability theory is the basis of the system security quantitative analysis, and it occupies a very important position in the safety system engineering.

The Cause and Consequence Analysis (CCA for short) is based on the quantitative analysis of reliability theory. It can qualitatively analyze the cause of the accident and the possible consequences of the incident. It can also quantitatively calculate the probability of occurrence of each event and the
risk rate of the consequences. Currently widely used in risk assessment and safety decision [3]. The CCA method is a combination of two system security analysis methods, the accident tree (FTA) and the event tree (ETA). Due to the complexity of the analysis and calculation process, there is less research in theory and application. In the process of actual use, the key issues such as unclear definition, logical confusion and unclear analysis are common in the selection of target systems, the determination of logical relationships in each link event, and the source of basic data in quantitative analysis. It leads to less attention to the details of the preparation, practicality, and low accuracy in the actual application, which brings a greater limitation to the application scope and effect of the CCA method [4]. Based on this, based on the systematic analysis of the CCA method, based on the system reliability theory, taking the motor overheating event as an example, the analysis process and application details of the CCA method are studied. At the same time, the risk of consequence events was calculated and evaluated based on the “Farmer Risk Assessment Chart”. The analysis and calculation of the CCA method and the clearness of the evaluation process contribute to the promotion of the CCA method in practical applications and the resolution of practical problems.

2. Related Reliability Theory
To conduct systematic, accurate cause-consequence analysis, reliability theory is the foundation. Reliability refers to the ability of the system to accomplish specified tasks within the specified time and under specified conditions. It is usually measured by reliability, including the reliability of human, a single machine, and system (subsystem).

The reliability of a single machine refers to the probability that the equipment, components, components, etc., will perform the prescribed function within the specified conditions and time [5], expressed as $R_M$. Reliability of the system (subsystem) depends on the reliability of each subsystem or component [6]. According to the logical relationship of each subsystem or component in the system, the corresponding logic operation is performed on its reliability, and the reliability of the entire system can be obtained.

3. Detailed Analysis Method and Process
A processing plant in China needs to introduce a motor system due to process improvement. CCA method is used to analyze the risk that the factory may be subject to. According to statistical data and literature [7], the failure probability of the heat dissipation system after motor overheating $P(B_0/A) = 0.02$, and no-failure probability $P(B_1/A) = 0.98$. In addition, the probability data of the initial events and other events need to be determined based on reliability theory.

3.1. Identify Evaluation Events
The system safety analysis is carried out in combination with the operating conditions of the field. It is considered that the energy forms involved in the operation of the motor mainly include electric energy, mechanical energy and heat energy. The main events that may result in more serious consequences are the electrification of the shell, the exposure of the rotating parts and the overheating of the motor. The three can be used as the evaluation event of the cause consequences analysis (the starting event). Here, the most common "motor overheating" event is chosen as the evaluation event, and the cause consequence analysis is carried out.

3.2. Drawing ETA and FTA
Fire is the most common cause of motor overheating [8]. Therefore, from the perspective of the “safety control of the system for the occurrence of a fire incident” in the process of “motor overheating and fire accident development,” the “motor overheating safety control system” is determined as the “target system”. By consulting the design and working principle of the target system and combining with the composition of the target system, the investigation and analysis of the working principle and safety measures of the target system were carried out around the initial event of “motor overheating”. The target system includes three parts: the motor cooling system, the fire extinguishing
system (artificial fire extinguishing and automatic fire extinguishing) and the fire alarm system after the failure. Finally, a reliability block diagram is drawn, as shown in figure 1.

![Motor overheating and fire system reliability block diagram](image)

Figure 1. Motor overheating and fire system reliability block diagram

From the initial events of the system, relying on the drawn system control chart, according to the sequential logic of the system components, from left to right, the success and failure of the two states are listed one by one for subsequent functional units. And get the binary state combination of all units. The motor overheating event tree is finally constructed.

According to the event tree drawn, the start event "motor overheating" and the intermediate failure event are respectively taken as the top event. Through investigation and analysis, the cause events and their logical relations related to the top event are obtained. Then expand the intermediate events and basic events to compile the corresponding accident tree diagram.

3.3. Drawing Cause - Consequence Diagram
Connect the event-tree and fault-tree to get a cause-consequence diagram, as shown in figure 2.

![Motor overheat cause – consequence diagram](image)

Figure 2. Motor overheat cause – consequence diagram

3.4. Calculating the Probability of a Consequence Event
According to the cause-consequence diagram, based on the theory of human reliability and equipment reliability analysis, we investigate and calculate the occurrence probability and related data of fault tree [9-10].

Among the causes of motor overheating, the first is "motor failure (X1)." The problem of motor failure rate should be attributed to the reliability of the equipment in the system reliability analysis. Therefore, it can be calculated based on the equipment reliability theory. The equipment reliability refers to the probability like the equipment, components, components, etc., have completed the prescribed functions within the specified conditions and time. It is expressed by $R_M$: 
\[ R_M(t) = e^{\int_0^t \lambda(t) dt} = e^{-\lambda t} \]  

(1)

Where: \( R_M(t) \) — reliability of a single machine; \( \lambda(t) \) — the time function of the failure rate; \( t \) — running time of the machine, h. Calculation of \( \lambda \):

\[ \lambda = K \lambda_0 \]  

(2)

Where, \( \lambda_0 \) is the basic frequency, \( K \) is the severity coefficient.

The initial reliability \( \lambda_0 = 1.43 \times 10^{-6}/h \) is initially determined. Combined with the environmental conditions of the motor, the severity coefficient \( K = 10 \). A survey of the company's motor management system shows that its maintenance cycle \( T = 6 \) months = 4320 hours. The substitution probability calculation formula obtains the maximum failure probability \( P(X_i) = 1 - e^{\lambda t} \approx \lambda_1 T_1 = 0.062 \). According to the same calculation method, the probability of other basic events can be obtained. Taking the motor overheating event as an example, the calculation method and results are shown in the table below.

**Table 1. Basic event probability data calculation (example)**

| Intermediate event          | Basic events of fault tree         | Probability of a basic event or equipment failure rate |
|-----------------------------|-----------------------------------|-------------------------------------------------------|
| Motor failure (X_1)         | Motor fault frequency: \( \lambda_1 = 1.43 \times 10^{-5}/h \); Set up maintenance cycle \( T_1 = 6 \) months = 4320h. Maximum failure probability \( P(X_1) = 1 - e^{\lambda_1 T_1} \) \( T_1 = 0.062 \) |
| Wiring defects (X_2)        | \( P(X_2) = 0.19 \) | Power failure rate \( \lambda_2 = 2.44 \times 10^{-5}/h \) (Maintenance cycle \( T_2 = 6 \) months = 4320h), Maximum failure probability \( P(X_2) = 1 - e^{\lambda_2 T_2} \) \( T_2 = 0.105 \) |
| Motor overheated (A)        | \( P(X_3) = 0.044 \) | Fuse failure frequency \( \lambda_3 = 1.62 \times 10^{-4}/h \) (Maintenance cycle \( T_3 = 1 \) month = 720h), Maximum failure probability \( P(X_3) = 1 - e^{\lambda_3 T_3} \) \( T_3 = 0.117 \) |

Secondly, based on the data in the table, using the calculation method of the incident probability of the top of the accident tree, it can be calculated that the occurrence probability of the start event and the link event of the event tree is: \( P(A) = 0.062/6 \) months; \( P(C_0) = 0.133/365h; P(D_0) = 0.044/2190h; P(E_0) = 0.065/1095h \).

The occurrence probability of five kinds of consequences events is calculated as:

1. \( P(G_1) = P(A)P(B_1/A) = 0.062 \times 0.98 = 0.062/6 \) months;
2. \( P(G_2) = P(A)P(B_2/A)P(C_1) = 0.092 \times 0.02 \times (1 - 0.133) = 0.0016/6 \) months;
3. \( P(G_3) = P(A)P(B_3/A)P(C_0)P(D_1) = 0.092 \times 0.02 \times 0.133 \times (1 - 0.044) = 2.3 \times 10^{-4}/6 \) months;
4. \( P(G_4) = P(A)P(B_4/A)P(C_0)P(D_0)P(E_1) = 0.092 \times 0.02 \times 0.133 \times 0.044 \times (1 - 0.065) = 10^{-5}/6 \) months;
5. \( P(G_5) = P(A)P(B_5/A)P(C_0)P(D_0)P(E_0) = 0.092 \times 0.02 \times 0.133 \times 0.044 \times 0.065 = 7 \times 10^{-7}/6 \) months.

**4. Calculate Risk Value**

According to the definition of risk value, the product of the probability of consequences and the loss of consequences is used directly as the risk value. Section 3.4 has obtained the probability of consequences. Then the consequence loss will be calculated.
Losses caused by accidents vary from person to person, and specific investigations should be conducted in conjunction with the company's own situation. The possible consequences of the overheating of the motor of the company and its losses are shown in table 2.

Table 2. Motor overheat consequences and loss table

| Consequence | Explain               | Direct loss | Shutdown loss | Total loss |
|-------------|-----------------------|-------------|---------------|-----------|
| G1          | Discontinued 2h       | 1000        | 2000          | 3000      |
| G2          | Discontinued 24h      | 15000       | 24000         | 39000     |
| G3          | Discontinued 1 month  | 1000000     | 744000        | 1744000   |
| G4          | Indefinitely discontinued | 10000000   | 10000000      | 20000000 |
| G5          | Indefinitely discontinued, 10 casualties | 40000000 | 10000000 | 50000000 |

Where, direct loss refers to the loss of property directly burned or caused. G5 also includes $300 thousand per person for casualty pension. Loss of work is the loss of $1000 per shutdown 1h. Loss of an unlimited period of production was about $1 million.

According to the survey of maintenance downtime or production time, casualties and property losses (including direct and indirect losses, etc.) are investigated for each corresponding consequences. Finally, risk value is calculated according to the formula (1), and the result is shown in table 3.

Table 3. Risk value of various consequences

| Consequence | Explain               | Direct loss | Shutdown loss | Total loss |
|-------------|-----------------------|-------------|---------------|-----------|
| G1          | Discontinued 2h       | 1000        | 2000          | 3000      |
| G2          | Discontinued 24h      | 15000       | 24000         | 39000     |
| G3          | Discontinued 1 month  | 1000000     | 744000        | 1744000   |
| G4          | Indefinitely discontinued | 10000000   | 10000000      | 20000000 |
| G5          | Indefinitely discontinued, 10 casualties | 40000000 | 10000000 | 50000000 |

5. Risk Assessment

Appraised by Farmer's Risk Assessment Chart. The figure shows the accident probability as the ordinate and the loss value as the abscissa. Using a curve (i.e., equal risk line) as a safety criterion, the coordinate plane is divided into two parts. The upper right side of the equal risk line is the high risk area, and the lower left is the low risk area.

(1) Determine the safety standards: According to the actual situation of the company, assume that the safety standard is $300/6 months.

(2) Make equal risk line: When logarithmic coordinates are used, the equal risk line appears as a straight line. Based on this, we made the "$300/ (6 months)" equal risk line, as shown in figure 3.
(3) Draw the accident risk point: Take the logistic value of the accident consequence $G_1$ to $G_5$ as the ordinate, and take the loss value as the abscissa, which is depicted in the risk analysis chart 3.

(4) Risk assessment: Select the consequences event where the risk point falls on safety risk standards, and propose corresponding countermeasures. As can be seen from the figure, if the $300/6$ month is used as a safety standard, the risk of other consequences except $G_3$ is acceptable. $G_3$ should be further proposed to take measures to reduce risk.

Of course, in the actual evaluation process, the selected safety standards are not the same, the analysis results are not the same. For example: if the sum of the risk ratios for various consequences does not exceed $1000/6$ months as a safety criterion, the above system may also be considered safe. Therefore, in the actual evaluation should fully consider the specific production conditions of different companies, and reasonably determine the risk standards.

6. Conclusions
(1) The CCA method lacks implementation details in actual use. There are widespread problems such as unclear selection of target systems, confusion in the logical relationship between link events, and unclear basic data sources such as failure rate and frequency of events. This limits the scope and effectiveness of the method.

(2) According to the system safety theory, the "motor overheating safety control system" was determined as the target system. Based on the reliability theory of people and equipment, a reliability block diagram is obtained according to the target system functions and control conditions. And draw the "motor overheating causes - consequences map." Clearly the logical relationship between the events. On this basis, based on the theory of human reliability and equipment reliability in system reliability analysis, the probability of incidents and the related data were investigated and calculated. The equipment failure rate and the probability of occurrence of each basic event, as well as the possible consequences and losses. Finally, the risk value is calculated and a risk assessment chart is drawn.

(3) The source of basic data in the quantitative calculation is studied in the reason-consequential analysis method. Based on the system reliability theory, the concrete feasible data determination method is proposed. However, since China has not yet established a complete human and aircraft reliability database, some of the data only originate from abroad. Adding technology and regional differences will, to some extent, affect the exact use of this method. Therefore, when using it, it should be corrected according to the actual situation.
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