CHEMICAL ENGINEERING TRANSACTIONS
VOL. 48, 2016

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Eddy de Rademaeker, Peter Schmelzer

ISBN 978-88-95608-39-6; **ISSN** 2283-9216
DOI: 10.3303/CET1648148

Research and Application of an Advanced LOPA Method for Risk Assessment of Chemical Process

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An advanced layers of protection analysis (LOPA) method is proposed in this study for assessing the risk associated with a chemical process. It is difficult to determine the values of the acceptable risk for accident scenarios and the probability of failure on demand (PFD) for emergency protection using the traditional LOPA method. Thus, based on an analysis of chemical accident statistics between 2001 and 2013 in China, we first established an acceptable risk function for chemical processes. We then demonstrated that the acceptable risk value for an accident scenario can be calculated by combining the acceptable risk function with the accident consequences evaluation method. The assessment index for an emergency system was developed to assess the protective function of emergency protection based on the analytic hierarchy process, and the PFD of emergency protection was obtained using a fuzzy comprehensive assessment method with fuzzy set theory, which completed the LOPA. The proposed method was applied to a methanol distillation installation. The acceptable risk value for an explosion scenario was 6.08×10^{-7} and the PFD for emergency protection was 1×10^{-2}. The efficiency of each type of independent protection was analyzed in the explosion scenario and the probability of mitigating the scenario was obtained by multiplying the PFDs for all of the independent protective layers. The result showed that the protection was sufficiently effective because the probability of mitigation by the different types of independent protection (1×10^{-8}), including emergency protection, was less than the acceptable risk value (6.08×10^{-7}). Thus, this advanced LOPA method is a powerful tool, which could improve the integrity and accuracy of traditional LOPA.

1. Introduction

Risk assessment is one of the most important methods for ensuring the safety of chemical processes (Wu, 2001). In order to control the risk associated with chemical processes, multiple protective measures are usually adopted to keep the residual risk lower than the acceptable risk based on the inherent safety design. Therefore, it is important to assess the efficiency of these protective measures to guarantee the safety of chemical processes.

The concept of "protections" and the layers of protection analysis (LOPA) method were both developed by the Centre for Chemical Process Safety (CCPS). In a specific accident scenario, the initiating event frequency, consequence severity, and the probability of failure on demand (PFD) for all of the independent protections are used to evaluate the possibility of accidents (CCPS, 2001). The effectiveness of protective measures is then evaluated by comparing the mitigated risk with the acceptable risk. The LOPA method is more objective and easier to use compared with qualitative evaluation methods (Summers, 2003). Thus, as a semi-quantitative risk assessment method, the LOPA method has become an important tool for risk analysis and evaluating chemical processes, as well as risk decision-making in recent years. To enhance its functions, LOPA is generally used with HAZOP, PHA, Bayes (Yun et al., 2009), Bow-tie (Markowski and Kotynia, 2011), or other methods (Argenti, 2015) to assess the risk associated with a chemical process.

The acceptable risk is known to be a key factor in the LOPA method. The acceptable risk, which is the maximum allowable probability of the accident consequences for a selected scenario, provides guidance when

Please cite this article as: Tong S., Wu Z., Wang R., 2016, Research and application of an advanced lopa method for risk assessment of chemical process, Chemical Engineering Transactions, 48, 883-888 DOI:10.3303/CET1648148

making risk decisions. The acceptable risk can be characterized by casualties, economic losses, or environmental damage (Lowrance, 1976). However, determining the acceptable risk is still uncertain during the safety process (Markowski et al., 2010) because it varies among countries due to political, economic, production, and other factors (Fischhoff et al., 1981). In general, the F-N curve method, ALARP criterion, cost-benefit analysis, and historical accident data statistics are used to obtain acceptable risk criteria (Cozzani et al., 2014). The accident data statistics method provides more objective and accurate results compared with the other three qualitative methods.

In addition, emergency protection is the last protective layer in a chemical process. The emergency system plays an important role in the risk control process and it can effectively prevent or control accidents (Fang and Mannan, 2007). However, it is difficult to determine the PFD of the protective layer in a quantitative manner due to the complex characteristics of an emergency. Therefore, the contribution of emergency protection to risk reduction in a chemical process is not included in the traditional LOPA. Obviously, ignoring the protective function of the emergency protective layer reduces the reliability of LOPA results. Thus, we propose an improved LOPA method, which considers the accident data statistics and emergency protection. The acceptable risk function is calculated based on an analysis of the accident statistics and the PFD of the emergency protection is determined by fuzzy comprehensive evaluation and using a trapezoidal fuzzy set method; thus, this advanced method is more accurate and comprehensive than the traditional method employed for chemical process risk assessments.

2. Basic principles of LOPA

In general, multi-layer protective measures are added to a chemical process to lower the risk. These protective measures are often called the protective layers or “protections” (CCPS, 2001). The safety function of these protections will greatly affect the safety integrity level of the chemical process.

Typical protections for a chemical process include the process design layer, basic process control system, process monitoring and artificial intervention layer, safety instruments system, mechanical protection layer, structure layer, and emergency system layer (Pasman and Reniers, 2014). As a semi-quantitative risk assessment method, LOPA typically uses order of magnitude categories that initiate the event frequency, consequence severity, and the likelihood of failure by independent protection layers (IPLs) to approximate the risk of a scenario. LOPA is usually applied based on a qualitative risk assessment (e.g., HAZOP). The probability of accident consequence C (such as a leakage, fire, or explosion) for the selected scenario is the product of the probability of occurrence for the initiating event and all of the independent protections for preventing the accident consequence. Thus, the probability of consequence C can be calculated according to Eq(1).

$$f^c = f^i \times \prod_{j=1}^{j} PFD_j \tag{1}$$

where f^c is the probability of accident consequence C, f^i is the probability of occurrence for the initiating event, and PFD_j is the PFD of the *j*th independent protection for preventing the accident consequence.

The probability of the accident scenario can be modified based on the probability of the focal consequence when further injury to a person due to the accident consequence is a concern. For example, people would be injured if they are exposed when an explosion occurs. The explosion could then cause an injury as a further accident consequence. The probability of a further accident consequence $f^{explosion-injury}$ can be derived by adding the probability of exposure by a person during the accident P^{exp} and the probability of a person being injured P^s (some may not be injured) to Eq(1), as shown by Eq(2).

$$f^{explosion-injury} = f^i \times (\prod_{j=1}^{j} PFD_{ij}) \times P^{exp} \times P^s \tag{2}$$

The risk of the chemical process will be considered unacceptable unless the probability of the accident consequence C is lower than the acceptable risk; otherwise, additional protections or measures should be considered to reduce the risk of the chemical process.

3. The acceptable risk function

For a selected scenario, LOPA requires a comparison of the probability of the accident consequence C with the acceptable risk in order to determine the adequacy of the protections. Based on the historical accident statistical analysis method, we propose an acceptable risk function for a chemical process to calculate the acceptable risk value.

First, we build an acceptable risk function T, where the independent variable is the consequence C of the accident and the dependent variable is the probability of the accident.

$$f \equiv T(C) \tag{3}$$

In this study, we selected the death of personnel as the consequence of the accident to build the acceptable risk function. Based on the statistical analysis of chemical accidents between 2001 and 2013, as well as a previous study (Kumamoto, 2007) and the standard severity classification for accident consequences, we divided the probability of the accident consequences into five levels, as shown in Table 1.

Table 1: Relationship between death number and probability

	Consequence level				
	Lower	Medium	Bigger	Major	Disastrous
Death number	$0<C_p\leqslant 1$	$1<C_p\leqslant 3$	$3<C_p\leqslant 10$	$10<C_p\leqslant 30$	$C_p > 30$
f_p (/year)	1×10^{-2}	1×10^{-3}	7.98×10^{-4}	6.85×10^{-5}	6.08×10^{-7}

The acceptable risk function can then be expressed as Eq(4).

$$f_P = T(C_P) = \begin{cases} 1.0\times10^{-2} & (C_P \le 1) \\ 1.0\times10^{-3} & (1 < C_P \le 3) \\ 7.98\times10^{-4} & (3 < C_P \le 10) \\ 6.85\times10^{-5} & (10 < C_P \le 30) \\ 6.08\times10^{-7} & (C_P > 30) \end{cases} \tag{4}$$

where C_P is the number of deaths caused by the accident consequence. However, it should be noted that there may be some deviations in the accident statistics due to objective reasons. Therefore, there may be some differences in the risk probability and the actual value of the risk function.

Thus, in order to obtain the acceptable risk for an accident scenario, we combine the chemical acceptable risk function and accident consequence evaluation method. According to the mathematical model of the accident consequence assessment, the affected area and the number of deaths can be analysed. Then, the acceptable risk value of a potential accident can be determined immediately according to Eq(4).

4. Quantization of Emergency protection

In order to quantify the protective function of emergency protection, we establish an evaluation index system for emergency protection based on the analytic hierarchy process (AHP) method, where the failure probability is obtained according to the fuzzy comprehensive assessment method and fuzzy set theory.

4.1 Assessment of emergency protection

According to the characteristics of the emergency protective layer, we build the evaluation index system for the emergency protection function, where the weight of each index is determined and the efficiency of the emergency protection is assessed by the fuzzy comprehensive evaluation method.

4.1.1 Evaluation index system of emergency protection

The emergency protection evaluation index system is built according to the emergency equipment, emergency personality, and emergency response, as shown in Figure .1.

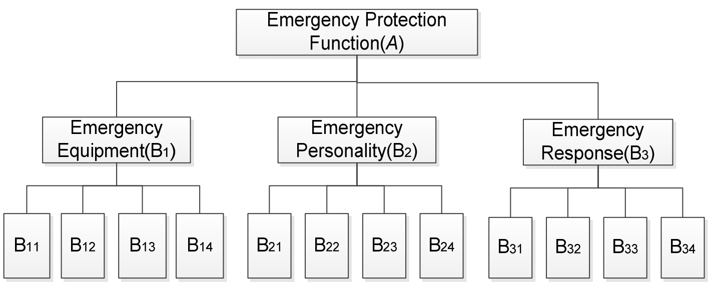

Figure 1: Index system of emergency protection evaluation

4.1.2 Building of factor set and decision set

According to the Figure.1, the factor sets $U = \{u_1, u_2, \ldots, u_n\}$ are built as follows.

$A=\{B_1, B_2, B_3\}$
$B_1=\{B_{11}, B_{12}, B_{13}, B_{14}\}$
$B_2=\{B_{21}, B_{22}, B_{23}, B_{24}\}$
$B_3=\{B_{31}, B_{32}, B_{33}, B_{34}\}$
$B_4=\{B_{41}, B_{42}, B_{43}, B_{44}\}$

The decision set has seven levels V= $\{V_1, V_2, V_3, V_4, V_5, V_6, V_7\}$. The evaluation index ranges between 0 and 100, and the value of each level is shown in Table 2.

Table2: Benchmark values for evaluation

NO.	Evaluation standard	Efficiency level of emergency protection
1	[90,100]	very high
2	[80,90)	higher
3	[70,80)	high
4	[60,70)	medium
5	[50,60)	Lower
6	[40,50)	Low
7	[0,40)	Very low

4.1.3 Calculation of Index weight

A matrix is built based on pairwise comparison among the indexes and their reciprocals. The normalized feature vector of the maximum eigenvalues is calculated to determine the weight of each index. The weight values of each index are listed in Table 3.

Table3: Description and weight of each index

Index	Description	Weight	Index	Description	Weight
B_1	Emergency equipment	0.2684	B_{22}	Emergency Operations	0.0657
B_2	Emergency person	0.1172	B_{23}	Emergency efficiency	0.0158
B_3	Emergency response	0.6144	B_{24}	Emergency techniques	0.0288
B_{11}	Communication equipment	0.0134	B_{31}	Emergency organism	0.0305
B_{12}	Fire-fighting equipment	0.1554	B_{32}	Emergency plan	0.1418
B_{13}	Reconnaissance equipment	0.0339	B_{33}	Emergency command	0.3654
B_{14}	Rescue equipment	0.0656	B_{34}	Emergency rescue	0.0767
B_{21}	emergency Knowledge	0.0069			

4.1.4 Fuzzy comprehensive evaluation

There is a fuzzy mapping from *U* to *V*, where $u_i \to f(u_i)=(r_{i1},r_{i2},\ldots,r_{im})\in F(V)$. The fuzzy mapping f can identify a fuzzy relationship $R_f(u_i,v_i)=f(u_i)(v_i)=r_{ij}$; therefore, R_f can be represented by a fuzzy matrix.

$$R=\begin{vmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{vmatrix} \tag{5}$$

Thus, a comprehensive evaluation can be performed.

4.2 PFD of emergency protection

It is still not possible to quantify the evaluation set for emergency protection efficiency, which includes high, higher, medium, lower, etc. Therefore, the fuzzy set theory is used to replace the fuzzy language and to calculate the fuzzy probability (see Figure.2).

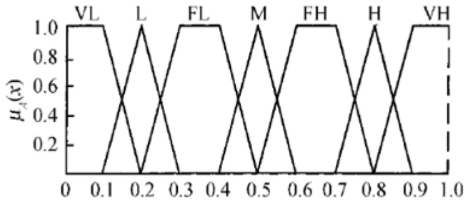

Figure 2: Trapezoidal fuzzy numbers of linguistic values

The trapezoidal fuzzy numbers and membership functions are given in Figure.2. The relation function for fuzzy number W (z) is given by Eq(6).

$$f_W(z) = \begin{cases} \frac{z-a}{0.1} & (a \le z < a+0.1) \\ 1 & (a+0.1 \le z \le b-0.1) \\ \frac{b-z}{0.1} & (b-0.1 \le z \le b) \\ 0 & \text{other} \end{cases} \quad (6)$$

where a is the lower bound of the fuzzy number in the natural language and b is the upper bound. In order to compare the risk probability, the fuzzy number of the expert judgment needs to be transformed into the corresponding fuzzy possibility score (FPS) (Khalil et al., 2013). The minimum and maximum fuzzy sets defined by the fuzzy maximum and minimum set are given by Eq(7) and Eq(8).

$$\mu_{min}(x) = \begin{cases} (1-x) & (0 < x < 1) \\ 0 & (\text{other}) \end{cases} \quad (7)$$

$$\mu_{max}(x) = \begin{cases} x & (0 < x < 1) \\ 0 & (\text{other}) \end{cases} \quad (8)$$

Next, the fuzzy probability of a fuzzy number can be obtained by Eq(9). F_{AL} and F_{AR} are the left and right fuzzy possible values.

$$FPS = [F_{AR} + 1 - F_{AL}]/2 \quad (9)$$

Finally, in order to ensure the consistency between the real and fuzzy probabilities of all events, it is necessary to transform the FPS into the fuzzy failure rate (FFR).

$$FFR = \begin{cases} 1/10^{k} & FPS \ne 0 \\ 0 & FPS = 0 \end{cases} \quad (10)$$

5. Application to a case study

The proposed method was applied to the risk assessment for a methanol distillation installation. According to the HAZOP results, the initiating event was the failure of the pump and the consequence was the explosion of the methanol distillation installation. Based on the consequence assessment model, the death radius of the explosion was 81.63 m and 62 people would die in the affected area. Thus, the level of the consequences was "Disastrous" and the acceptable risk was 6.08×10^{-7}/year (Table 1).

Next, five expert groups including safety, chemical engineering, fire, emergency, and management were selected to evaluate the performance of the emergency. The fuzzy comprehensive assessment results were very high, high, medium, higher, and high. The weights given by the five expert groups were calculated using the AHP method. After the comprehensive treatment, the relationship function for the total fuzzy number W was determined according to Eq(11).

$$f_W(x) = \begin{cases} \frac{x-0.595}{0.09} & (0.595 \le x < 0.685) \\ 1 & (0.685 \le x \le 0.54) \\ \frac{0.62-x}{0.08} & (0.54 < x \le 0.62) \\ 0 & \text{other} \end{cases} \quad (11)$$

According to Eq(6) to Eq(11), F_{AL}=0.574, F_{AR}=0.628, FPS=0.527, and FFR=0.01.The fuzzy failure probability for the emergency protective layer was 1×10^{-2}. All of the independent protections and their PFDs are listed in Table 4. The probability of exposure for a person and the occurrence of injury were both 1.0.

Table 4: Assessment records of the LOPA

1	2	3	4	5	6	7	8	9
Initiating event	Consequence severity	Consequence level	Acceptable risk	BPCS	Process monitor	SIS	Relief valve	Emergency
Pump failure 1×10^{-1} /year	Overpressure explosion 62 person died	Disastrous	6.08×10^{-7} /year	PFD 1×10^{-1} /year	PFD 1×10^{-1} /year	PFD 1×10^{-2} /year	PFD 1×10^{-1} /year	PFD 1×10^{-2} /year

According to Eq(2), the probability of the explosion of the methanol distillation system was 1×10^{-8}/year and the maximum allowable probability (acceptable risk) was 6.08×10^{-7}/year, so the risk was acceptable. However, if there was no emergency protective layer, the probability of the explosion was 1×10^{-6}/year, which was greater than the maximum allowable probability, so the risk was not acceptable. This demonstrates that the emergency protective layer can be effective in reducing the risk of a chemical process.

6. Conclusions

In the present study, an advanced LOPA method was proposed that considers the acceptable risk and emergency protection when assessing the risk of a chemical process. This advanced method improves the traditional LOPA method by determining the acceptable risk of accident consequences for a selected scenario and by calculating the PFD for the emergency protective layer.

The acceptable risk function was established based on the statistical analysis of historical chemical accidents. The accident data statistics method provides more objective and accurate results compared with other qualitative methods. Thus, the acceptable risk of an accident scenario can be calculated by combining the acceptable risk function with the accident consequence evaluation method. The acceptable risk of an accident consequence can then be determined immediately according to the acceptable function.

The PFD of the emergency protection was calculated according to a fuzzy comprehensive evaluation and a trapezoidal fuzzy number method. The protective efficiency of the emergency protection was evaluated by fuzzy comprehensive evaluation. Fuzzy set theory was used to replace the fuzzy evaluation language and to transform the FPS into the FFR. The application of this approach to a study case demonstrated that the results obtained by the advanced method were more accurate and comprehensive than those produced by the traditional method during risk assessments of chemical processes.

Acknowledgments

The research work was supported by National Science and Technology Foundation of China under Grant No. 2015BAK16B03.

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