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Continuous improvement strategies for environmental risk mitigation in chemical plants

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Abstract

Environmental risk management for chemical plants usually requires appropriate data resources and decision-making methods. To mitigate environmental risks in industrial practices, technologies and measures should be evaluated based on cost, health, and ecosystem considerations. This work proposes an integrated framework for designing continuous environmental risk mitigation strategies in chemical plants. Firstly, we established a general and hierarchical indicator system to identify the risks which come from inherent process safety and operational management, chemicals storage, and transportation. Subsequently, we proposed a qualitative analysis method for identifying risk points that could potentially result in health and environmental accidents. Then, we quantitatively analyzed the risk points by using the best-worst method (BWM). This BWM enables the users to obtain the critical values (weights) of each risk point. Technologies and measures to mitigate environmental risk can be evaluated and prioritized. Additionally, we propose a method for evaluating the costs and implementation durations. Finally, we studied a pharmaceutical intermediate plant to demonstrate the feasibility of the proposed framework.

Keywords: Best-Worst method; Environmental risk; Chemical plant; risk assessment

1. Introduction

Owing to the rapid development of technology, chemical plants tend to produce diverse products and have more complex configurations. In most chemical plants, distant control systems have been deployed to eliminate the risks incurred by the workers. However, there are still many unsafe factors in the production of chemicals. For example, the raw materials, intermediates, and final products in the chemical production process may be flammable, explosive, toxic, or corrosive. High-temperature or high-pressure equipment is usually deployed in chemical plants. Moreover, different plants that produce the same products have different risk levels because of the expertise of the workers and management. The above factors could cause great harm to operators, bring economic loss to plants, and result in the environment damage of the surrounding environment. According to relevant reports, there were 28 chemical explosion accidents and 82 deaths in China in 2018. In April 2019, the "March 21" Xiangshui explosion in Jiangsu Tianjiayi Chemical Co., Ltd caused the death of 78 people (Wikimili, 2019). Therefore, the occurrence of chemical accidents calls for an integrated method to identify and mitigate the risks in chemical plants.

- Process safety-driven environmental risk management

Many methods have been proposed to reduce the risks and ensure safe production in industrial plants. By integrating risk analysis in the optimization formulation, Jung et al. (2010) presented a new approach to optimize facility layout for toxic release. Tan et al. (2016) extended the pinch analysis into the area of environmental security risk management. Analytic hierarchy process (AHP) was used to determine the criticality of each risk point in the first step. Next, extended pinch analysis was introduced to find the minimum value for the willingness of the plant management to pay or budget relative to benefits with respect to risk or pollutant reduction. Wang et al. (2017) proposed a segmented pinch analysis methodology that considers the relationship between environmental risk prevention and control countermeasure costs while also considering the criticality of environmental risk prevention. The final optimal mix of countermeasures can then be determined from candidate solutions. This enables a firm to best allocate resources to the risk points to ensure the normal operation of the chemical plant. To analyze adverse environmental events, data provided by different sources and geographically dispersed repositories have also been considered. Ciarapica et al .(2019) developed a conceptual model based on association rules (AR) to investigate the network of influences among data collected. Moreover, a social network analysis has been used to represent the association rules, providing a complete overview of the factor interaction and identifying communities of nodes to define local and global patterns and locate influential entities. Abrahamsen et al. (2018) studied the ALARP (as low as reasonable and feasible) principle which is broadly used in safety management decision-making. In this study, we examine the energy production sector of the chemical industry and argue that, depending on the decision context, the application of the ALARP principle is not always appropriate. Conversely, a dynamic interpretation, in which decisions oscillate between two borderlines (in one case reference is made to expected values and in the other one to the precautionary principle) is more appropriate.

- Best-worst method (BWM)

BWM is a new method proposed by Rezaei in 2015 for solving multi-criteria decision-making (MCDM) problems. In an MCDM problem, a number of alternatives are evaluated with respect to a number of criteria to select the best alternative(s). According to BWM, the best (e.g. most desirable/important) and the worst (e.g. least desirable/important) criteria are identified first by the decision-maker. Pairwise comparisons are then conducted between each of these two criteria (best and worst) and the other criteria. A maximin problem is then formulated and solved to determine the weights of different criteria. To show the applicability of this new method, Razaei posed a real-world decision-making problem, selecting a mobile phone, using a sample of university students. He also compared the results of BWM with AHP considering a number of evaluation criteria and demonstrated that BWM performs better than AHP. BWM has several salient features that make it a robust and interesting method (Rezaei, 2015):

(1) BWM is a vector-based method that requires fewer comparisons compared to matrix-based MCDM methods such as AHP.

(2) The final weights derived from BWM are highly reliable as BWM provides more consistent comparisons compared to AHP. While in most MCDM methods (e.g. AHP), the consistency ratio is a measure to check if the comparisons are reliable or not, in BWM the consistency ratio is used to see the level of reliability as the output of BWM is always consistent.

(3) Not only can BWM be used to derive the weights independently, but it can also be combined with other MCDM methods.

(4) In BWM, only integers are used, making it much easier to use.

Based on the above advantages of BWM, in the past, BWM has been widely used in various fields. Rezaei (2016) proposed an innovative three-phase supplier selection methodology including preselection, selection, and aggregation. Conjunctive screening is used for preselection; namely, the BWM method is introduced for the selection phase. Setyono et al. (2018) applied BWM to vendor selection, using the XYZ mining company in Indonesia as a case study. The results showed that the method of retrieving data from transaction history, survey data from various sources, and process it with BWM is convenient in measuring vendor evaluation values. Malek et al. (2019) prioritized the sustainable manufacturing barriers by calculating their weights through the application of BWM in a manufacturing organization in India. Gupta et al. (2017) applied BWM to address many of the barriers to energy conservation or energy efficiency. BWM multi-criteria decision making was used to rank the barriers. The results showed that the economic, governmental, and technological barriers are the most prominent. The results shall be of great help in decision making regarding the improvement and development of energy-efficiency measures in buildings. With the help of decision-makers, a roadmap is developed to help overcome these barriers over long, medium, and short-term durations, respectively. In this study, BWM is used to quantify the risk of plants. The criticality (optimal weight) of the risk points is determined by BWM. The risk points are ranked according to the size of the critical value, indicating the risk degree of the risk points.

The main purpose of this paper is to reduce risk in the process of chemical production. First, we propose a general and hierarchical indicator system for recognizing the risks from inherent process safety and operational management to chemicals storage and transportation. Next, we quantify these risk points by BWM according to the possibility for health-related and environmental accidents. Simultaneously, we estimate the cost and implementation duration. Finally, considering the criticality of each risk point, the countermeasure cost, and the duration, we present the implementation roadmap to environmental risk mitigation. Through the roadmap, the most critical points of the plant are gradually controlled and managed, and the safety production standard is finally achieved.

2. Methodology

Integrated framework for environmental risk management

In this study, we propose an integrated framework for environmental risk management, as shown in Fig.1. The risk points in the plants are recognized and then the critical values (optimal weight) of the risk points are quantified by the BWM. The order of these risk points can be determined based on an index that is determined by the critical values, countermeasure cost, and implementation durations. This sequence could help decision-makers resolve the risk points in the most appropriate way by reducing the overall risk of the plants, or minimizing the overall risk of the plants under the limited countermeasure cost.

2.1 Safety checklist and fault tree analysis (FTA)

The most effective tool for safety checks is a safety checklist. Fault tree analysis quantitatively analyzes and identifies many accident-causing factors, investigates the main causes of accidents, and provides a scientific basis for formulating preventive measures. According to the production characteristics of chemical plants, an expert investigation method is used to find hidden safety faults in the production process and establish a safety checklist to eliminate shortfalls. The sub-risk points in the production process are identified by using FTA.

2.2 Indicator system and BWM

In this study, the principles for the identification of risk factors mainly refer to the

Risk Assessment Guideline for Chemical Material and Chemical Products Manufacture (2018). The indicators can be classified into eight types including policy, business, and management risk. For each category, sub-indicators can be defined. The 25 sub-indicators we considered are summarized in Table 1.

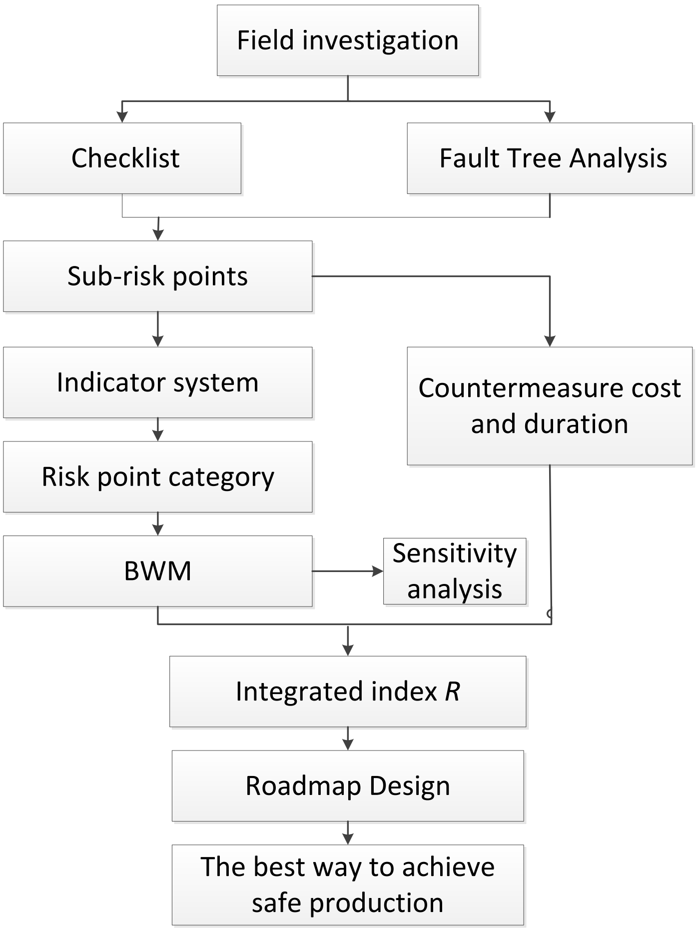

Fig. 1. Integrated framework for environmental risk management.

The steps involved in BWM (Rezaei, 2015) are described below.

Step 1: Determination of selection or decision criteria. In this work, we determined a set of n criteria $\{C_1, C_2, \ldots, C_n\}$ through literature review and discussions with relevant experts.

Step 2: Identification of the best and worst criteria among all the criteria using experts' opinions.

Step 3: Quantification of the best-selected criteria over other criteria based on a scale of 1-9. The resultant vector is presented below:

$$A_B = \{a_{B1}, a_{B2}, \ldots, a_{Bn}\},$$

where a_{Bj} indicates the preference of the best criteria B over criteria j. Note that a_{BB}=1.

Step 4: Quantification of the worst criteria over other criteria based on a scale of 1-9. The resultant vector is presented below:

$$A_W=\{a_{1W}, a_{2W}, \dots , a_{jW}\}^T,$$

where a_{jW} indicates the preference of the criteria j over the worst criteria W, anda_{WW}=1.

Step 5: The optimized weights (w_1^*, w_2^*, … , w_n^*) are determined such that the maximum absolute differences of all j are minimized by the following set $\{|w_B-a_{Bj}w_j|\},\{|w_j-a_{jW}w_W|\}$.

The above can be represented by the following model:

$$\min\max\{|a_B-a_{Bj}W_j|,|W_j-a_{Jw}W_W|\}$$
$$\text{s.t.}\sum_j w_j=1 \qquad (1)$$
$$w_j\geq 0, \text{ for all } j$$

Equation (1) can be solved by converting it into the following linear programming problem model:

$$\min \xi^L$$
$$\text{s. t.}$$
$$|w_b- a_{Bj}w_j|\leq\xi^L, \text{ for all } j$$
$$|w_j-a_{jW}w_W|\leq\xi^L, \text{ for all } j \qquad (2)$$
$$\sum_j w_j=1$$
$$w_j\geq 0, \text{ for all } j$$

The optimal weights (w_1^*, w_2^*, … , w_n^*) and optimal value ξ^L are computed by the linear model (2). After obtaining the weights for each, it is necessary to check the consistency level of the comparisons. Consistency of the comparison depends on the value of ξ^L; a value close to 0 indicates high consistency Values below 1 indicate consistent comparison.

2.3 Integrated index R

The integrated index R is a function of three factors: the critical values of sub-risk points (C), the countermeasure cost for resolving sub-risk points (I), and the implementation duration required for resolving sub-risk points (T). The critical value of the sub-risk point is determined by BWM. Referring to the concept of project life cycle, the implementation duration T is defined as the total duration of a project from beginning to end, including four stages: identifying requirements, proposing solutions, executing projects, and ending projects.

$$R=I*T/C \tag{3}$$

After several adjustments during the analysis process, we found that the comprehensive consideration of each sub-risk point by exponential R is the best only in the case of Eq. (3),. The smaller the value of R is, the less the cost and duration needed to resolve the sub-risk points and the larger the critical value to be calculated. Therefore, sub-risk points with small R should be resolved first. We can then reduce the risk of the plant according to the priority of sub-risk points.

2.4 Roadmap

The optimal weight and ranking of each risk point are determined by BWM, but because of funding problems or the nature of the risk point, risk points cannot be resolved at the same time. Therefore, considering the criticality of risk points, countermeasure cost, and durations, we present the implementation roadmap to environmental risk mitigation. The roadmap provides the optimal sequence for resolving sub-risk points. In the roadmap, the critical value, countermeasure cost, and implementation duration of the sub-risk points are graphically expressed. The decision-makers choose the best way to reduce risk using the roadmap.

Table 1 Risk indicator system at the plant level

Indicator	Sub-indicator	Benchmark
Policy risk	policy analysis	National Industrial Structure Adjustment Guidance Catalogue”(2014) and local industrial structure adjustment guidance catalogue
Operating risk	Business licenses	Business license, organization code certificate, tax registration certificate, license to produce and operate specific products, etc.
	Basic information	< basic information table>
	Main project operation years	Y= evaluate time- established time（modification time）
	Rate of operation	K= last year's production/ design scale
	Ethical risk	Financial statements (including balance sheet, income statement and cash flow statement)
Management risk	Production safety management system	The implementation of the safety management policy
	Investment in production safety	A= investment in production safety / saleroom
	Fire management	Fire protection system is deployed
	Environmental pollution regulation	Consult environmental pollution accident preplan document
	Safety training	safety training management system, training plan, and training record
Process risk	Manufacturing technology	Whether it is flammable, explosive, drama drugs, corrosion products
		q/Q
		T
		P
	Main workplace	<FSR>and the main project design/ installation company qualification
	Environmental protection project	<FSR>and environmental protection acceptance report
		Accident poll
	Equipment and operation	Whether the general operator has the post certificate
		Whether operators are qualified to operate related equipment

		Whether the purchased equipment and accessories are qualified by relevant departments
		Whether buildings and equipment are equipped with appropriate lightning protection facilities
		Whether the equipment has adopted anti-static measures
		Whether the equipment and circuit are explosion-proof facilities
		Whether monitoring, early warning, protection equipment and facilities are complete
Storage and transportation risk	Fire protection measures in storage area	Whether the fire dike is effective
	Handling risk	Whether the system is complete and whether it is strictly implemented
Industrial risk	Historical accident records of the plant within five years	The Safety Production Law of the People's Republic of China (revised in 2014) Accident Record of Safety Production Responsibility
		Have there been any environmental pollution incidents in history
Standard rating risk	ISO14000 Environment Management System Certification	Whether ISO14000 Environmental Management System Certification is sound
	Safety standardization	Whether the plant has the safety production standardization certificate and plaque issued by the safety supervision department or the designated evaluation organization unit
Environmental sensitive risk	Environment (level 1 risk)	within 5 kilometers
	Chemical industrial park	Yes/ no
Natural disaster risk	Geological hazard risk	Geological condition analysis and historical geological disaster record of the area where the plant is located
	Meteorological risk	Analysis of meteorological conditions and records of historical meteorological disasters in the area where the plant is located
	Other unexpected risks	Analysis of other sudden accidents and historical records of other sudden accidents in the area where the plant is located

3. Case study

3.1. Production process description

The case study is based on a chemical plant that produces pharmaceutical intermediates. The main product is pyrocatechol monoethyl ether. Its production process is shown in Fig. 2.

β- benzyl alcohol, the raw material, is fed into the reactor with sodium hydroxide and methyl ethyl benzene. The temperature is raised first to 95 °C. Afterwards, the reactor is cooled to 57–59 °C, and ethyl ether is discharged for subsequent distillation. During the nitration reaction stage, the temperature is reduced to 0 °C, and the stream is filtered after the reaction to obtain the nitro compound. During the reduction reaction stage, the ethyl ether is dried using anhydrous sodium sulfate, yielding amino compounds. Finally, at the hydrolysis reaction stage, the compounds are dried at 0 °C to remove the ethyl ether, and pyrocatechol monoethyl ether is obtained by distillation and separation (Wang et al., 2017).

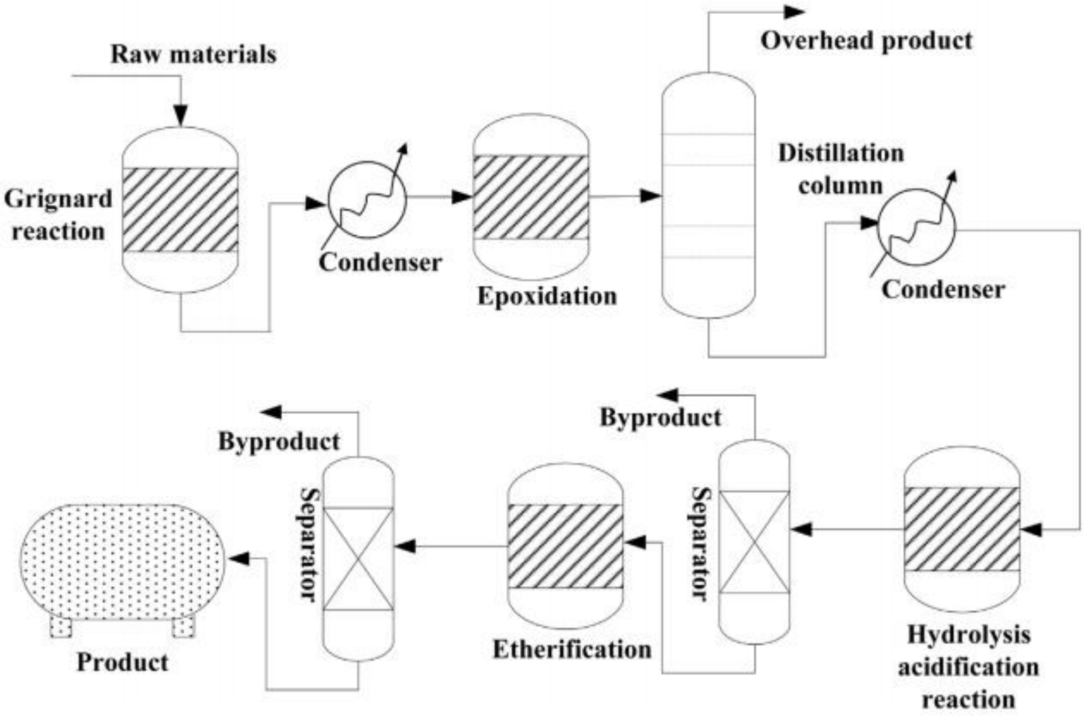

Fig. 2. Process diagram of pyrocatechol monoethyl ether production.

3.2. Determining risk points and sub-risk points

According to the production characteristics of the chemical plant, the sub-risk points in the production process are identified by using expert investigation, a safety checklist and FTA (Wang et al., 2017), and an plant risk-indicator system established to classify sub-risk points into different safety aspects (risk points) based on the similarity of their nature. After expert investigation and FTA identification, we identified a total of 11 sub-risk points for the plant. These sub-risk points are divided into three types: management risk, process risk and storage and transportation risk. The risk points and sub-risk points are shown in Table 2.

Table 2 Risk points and sub-risk points

Risk point	Sub-risk point
Management risk (C_1)	Lack of safety awareness and security management structure flaws in plants (E_1) Labor supplies and goods not standardized (E_2) Poor environment, multiple damaged roads (E_3) Lacking signs marking escape route and a mix of warning signs (E_4)
Process risk (C_2)	No water level detection device (M_1) Accident emergency pool pumps are seriously eroded (M_2) No organized emission source (M_3) Lack of reserve facilities for environmental emergency supplies (M_4) Lack of safety warning signs and protective equipment (M_5)
Storage and transportation risk (C_3)	No intermediate tank storage (G_1) Inadequate warehouse area for hazardous waste storage (G_2)

Table 3 Scale for pairwise comparison

Intensity of importance	1	2	3	4	5	6	7	8	9
Definition	Equal importance	Weak	Moderate importance	Moderate importance	Strong importance	Strong plus	Very Strong importance	Very, very strong importance	Extreme importance

Table 4 Best-to-others (BO) and others-to-worst (OW) pairwise comparison for risk points

BO	C_1	C_2	C_3
$Best\ risk\ point: C_2$	3	1	5

OW	$Worst\ risk\ point: C_3$
C_1	2

C_2	7
C_3	1

Table 5 Optimal weights of risk points

Risk point	Optimal weight	ξ^L
Management risk (C_1)	0.225	0.025
Process risk (C_2)	0.65	
Storage and transportation risk (C_3)	0.125	

3.3 Determining the critical values of risk points and sub-risk points

The data were determined by the Delphi method. Experts were asked to give pairwise comparison ratings for each risk point and sub-risk point and agree to a common rating after discussion among them. An interpretation of the scale used is presented in Table 3 (Gupta et al., 2017). Where pairwise comparison is done among various criteria, suppose ‘a’ is a criterion; then, $a_{ij} = 1$ shows equal importance of criteria *i* over *j*, and if $a_{ij} > 1$ it shows high importance of *i* over *j*. This study uses pairwise comparison of risk points as an illustrative example. The results of the pairwise comparison of the risk points are presented in Table 4.

In step 5, we obtained the optimal weights for each risk point and sub-risk point by solving model (2). The optimal weights of risk points and corresponding consistency values are represented in Table 5. The results of the pairwise comparison of all the sub-risk points are shown in Tables 6. Additionally, we multiplied the optimal weights of the risk points with the optimal weight of the sub-risk points below it to estimate the global weights of each sub-risk point (see Table 7). A value of 0.025 indicates high consistency.

Table 6 Best-to-others (BO) and others-to-worst (OW) pairwise comparison for sub-risk points

BO	E_1	E_2	E_3	E_4
$Best\ risk\ point: E_3$	2	7	1	4
OW	$Worst\ risk\ point: E_2$			
E_1	3			
E_2	1			
E_3	7			
E_4	2			

BO	M_1	M_2	M_3	M_4	M_5
$Best\ risk\ point: M_3$	3	4	1	2	8
OW	$Worst\ risk\ point: M_5$				
M_1	3				
M_2	2				
M_3	8				
M_4	4				
M_5	1				

BO	G_1	G_2
$Best\ risk\ point: G_1$	1	2
OW	$Worst\ risk\ point: G_2$	
G_1	2	
G_2	1	

Table 7 weight and ranking of risk points and sub-risk points

Risk point	Risk point weights	Sub-risk point	Sub-risk point weights	Global weights	Ranking
Management risk (C_1)	0.225	E_1	0.255	0.057	7
		E_2	0.078	0.018	11
		E_3	0.529	0.119	3
		E_4	0.137	0.031	10
Process risk (C_2)	0.650	M_1	0.153	0.099	4
		M_2	0.115	0.075	6
		M_3	0.448	0.291	1
		M_4	0.230	0.150	2
		M_5	0.055	0.036	9
Storage and transportation risk (C_3)	0.125	G_1	0.667	0.083	5
		G_2	0.333	0.042	8

Table 8 Critical value changes of each risk point through sensitivity analysis

Risk point	Normalized Weight	Modified weights of all risk points when modifying management risk from 0.1 to 0.9								
Management risk	0.650	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Process risk	0.225	0.579	0.514	0.450	0.386	0.322	0.257	0.193	0.129	0.064
Storage and transport risk	0.125	0.321	0.286	0.250	0.214	0.179	0.143	0.107	0.071	0.036

Table 9 Ranking of various risk points through sensitivity analysis

Sub-risk point	Run0.1	Run0.2	Run0.3	Run0.4	Run0.5	Run0.6	Normalized (0.620)	Run0.7	Run0.8	Run0.9
M_1	9	9	8	7	6	5	4	3	3	3
M_2	10	10	10	9	8	6	6	5	4	4
M_3	7	5	3	2	1	1	1	1	1	1
M_4	8	7	6	5	4	2	2	2	2	2
M_5	11	11	11	11	10	10	9	8	7	5
E_1	3	3	4	4	5	7	7	7	8	8
E_2	6	8	9	10	11	11	11	11	11	11
E_3	1	1	1	1	2	3	3	4	5	6
E_4	5	6	7	8	9	9	10	10	10	10
G_1	2	2	2	3	3	4	5	6	6	7
G_2	4	4	5	6	7	8	8	9	9	9

The global weight represents the risk degree of the sub-risk points. The bigger the global weight is, the higher the risk degree of the sub-risk point is. The greater the probability of accidents, or the more serious the consequences of accidents are, the greater the losses to people, plants, and the environment are. On the contrary, the smaller the global weight is, the lower the risk degree of the sub-risk point is. For example, the global weight of M_3 is 0.291, which is the highest global weight among the 11 sub-risk points, indicating that M_3 is the sub-risk point with the highest risk degree and the most urgent to be resolved. The global weight of E_2 is 0.078, which is the lowest value of the risk degree; therefore, E_2 has little impact on the overall risk degree of the plant. In case of insufficient funds or other necessary circumstances, resolution of this risk point can be postponed.

If there are sufficient funds, the plant can achieve safe production in the shortest time and the easiest way possible. In the case of insufficient funds, the managers and decision-makers can control and govern the risk points according to the countermeasure cost and the roadmap. The maximum safety production is achieved using limited resources and the safety risk management standard will be achieved as well.

3.4 Sensitivity analysis

Sensitivity analysis was performed to check possible biasness in results and to filter out any effect of the highest-weights enabler on other enablers in study (Gupta et al., 2017). In sensitivity analysis, we vary the weights of all the factors in the study proportionally to the weight variation of the top ranked enabler. When varying the management risk weight from 0.1 to 0.9, the weights of all the risk points varied accordingly (see Table 8). Table 9 indicates the ranking of these risk points based on the weights obtained in Table 8. The results of the sensitivity analysis indicates indicate that the BWM results are unbiased obtained through BWM are free from any bias and results areand consistent, even whenif there is variation in the weights of one enabler. Fig. 3 illustrates the sensitivity analysis.

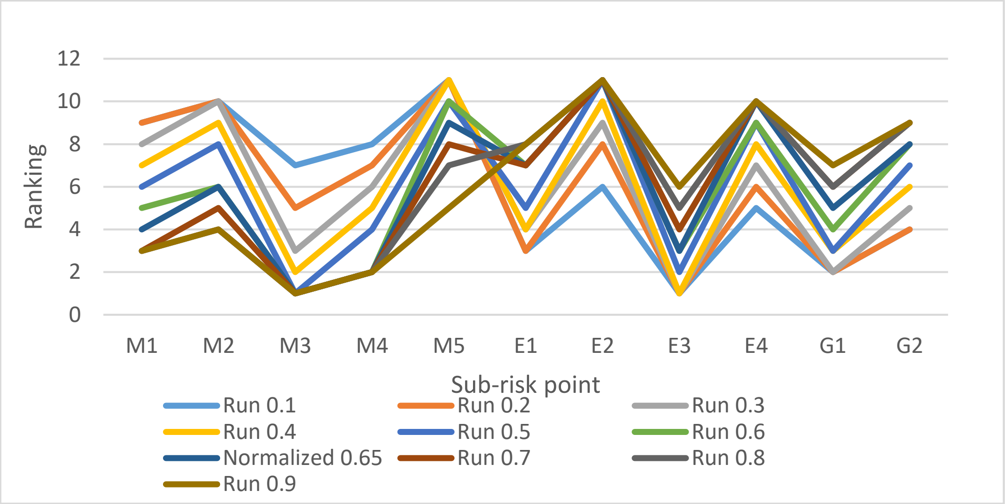

Fig. 3. Sub-risk point ranking by varying risk point weights.

3.5 Roadmap

Owing to the manpower, countermeasure cost, and time issues, we may not be able to resolve all sub-risk points at once. Therefore, in this study, we consider the roadmap of the identified risk points. The aim is to find the most reasonable way to resolve the sub-risk points in the shortest time or at the lowest cost. The difficulty of resolving sub-events is mainly determined by the countermeasure cost and the time required. The main purpose of this study is to reduce the risk, which is related to the critical value of sub-risk points, in the production process of chemical plants. Therefore, when analyzing the roadmap of sub-risk points, we mainly consider the time, cost, and critical value. We compute the critical values of the sub-risk points by BWM. The countermeasure cost and time required are shown in Table 10.

Table 10 sub-risk point weights, countermeasure cost and implementation durations

Sub-risk point	Critical values	Countermeasure cost (10^4 yuan)	Implementation durations (month)
Lack of safety awareness and security management structure flaws in plants (E_1)	0.057	11	12
Labor supplies and goods not standardized(E_2)	0.018	1	1
Poor environment, multiple	0.119	2	4

damaged roads (E_3)			
Lacking signs marking escape route and a mix of warning signs (E_4)	0.031	0.2	0.5
No water level detection device (M_1)	0.099	4	2
Accident emergency pool pumps are seriously eroded (M_2)	0.075	6	2.5
No organized emission source (M_3)	0.291	56	4
Lack of reserve facilities for environmental emergency supplies (M_4)	0.150	120	3
Lack of safety warning signs and protective equipment (M_5)	0.036	79.8	3
No intermediate tank storage (G_1)	0.083	184	1.5
Inadequate warehouse area for hazardous waste storage (G_2)	0.042	336	10

Table 11 Order of sub-risk points

Sub-risk point	E_1	E_2	E_3	E_4	M_1	M_2	M_3	M_4	M_5	G_1	G_2
T (month)	12	1	4	0.5	2	2.5	4	3	3	1.5	10
I (10^4 yuan)	11	1	2	0.2	4	6	56	120	79.8	184	336
C	0.057	0.018	0.119	0.031	0.099	0.075	0.291	0.15	0.036	0.083	0.042
R	2316	56	67	3	81	200	770	2400	6650	3325	8000
Order	7	2	3	1	4	5	6	8	10	9	11

We have plotted the graph of the degree of difficulty in resolving sub-risk points using the implementation duration as the horizontal coordinate and the cumulative cost as the vertical coordinate, as shown in Fig. 4. Sub-risk points E_4, E_2, M_1, and M_2 in the blue region are the ones that can be resolved with less expenditure in the short term, while sub-risk points G_1, M_4, M_5, M_3, and E_3 in the yellow region are the ones with higher cost or long-term resolution time. Sub-risk points G_2 and E_2 in the red region are the ones with much higher cost or much longer resolution time. By solving Eq. (3), we obtain the priority order of the sub-risk points. The index R and the order are shown in

Table 11.

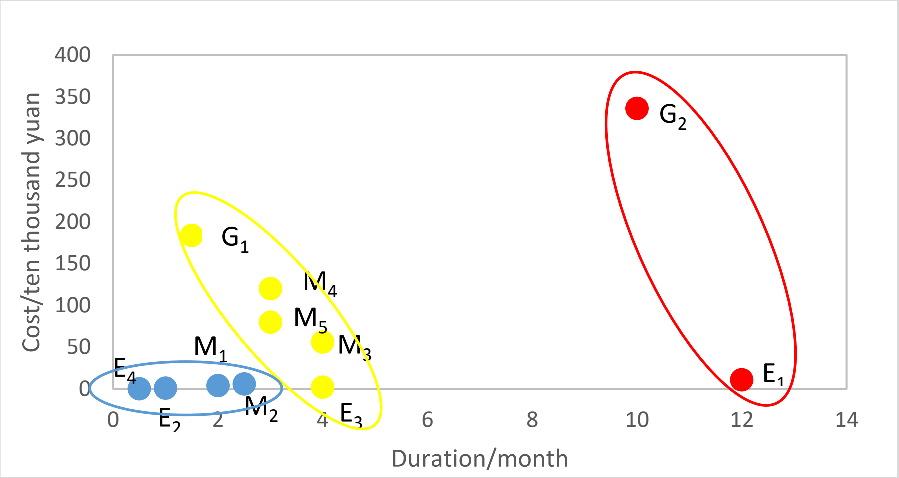

Fig. 4. Countermeasure cost and as a function of the implementation duration.

We determined the resolution order of the sub-risk points according to Table 11, and then estimated the countermeasure cost and critical value. Finally, we plotted the roadmap using the critical value as the horizontal coordinate and the countermeasure cost as the vertical coordinate (see Fig. 5).

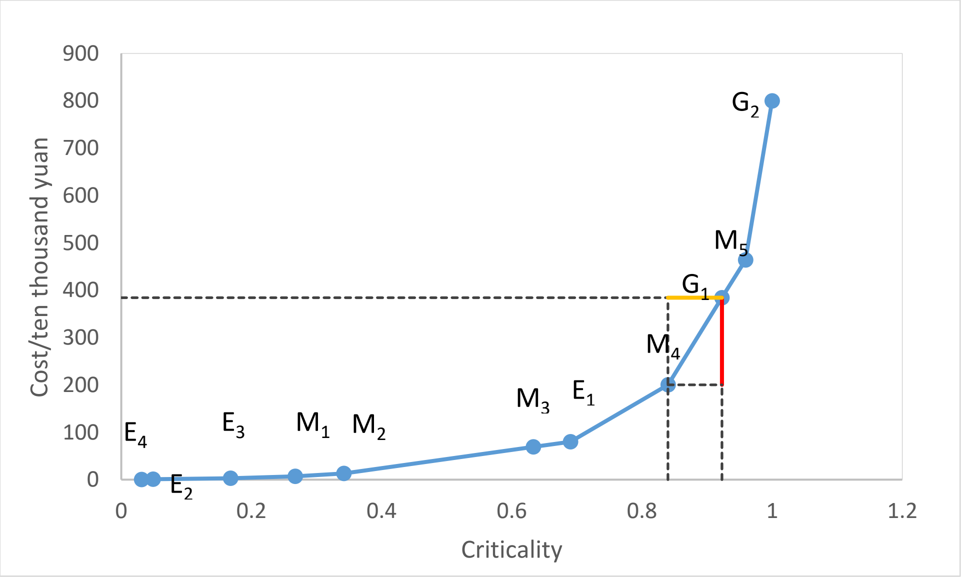

Fig. 5. Roadmap

In Fig.5, the yellow line segment is the solvable critical value of sub-risk point G_1, which is the reduceable chemical plant risk. The red line segment is the countermeasure cost needed to resolve sub-risk point G_1.

The chemical plant decision-maker can prioritize the resolution of sub-risk point E_4, with a criticality of 0.031, at a cost of 0.22 million yuan.. Then, $E_{2,}$ with a criticality of 0.018, can be resolved at a cost of 10,000 yuan. By analogy, the last sub-event to be resolved is G_2. The total resolution cost is 8 million yuan and the total resolved criticality is 1. At this time, the plant is in a safe production state. In the case of a limited capital, for example, the safety production investment is 4 million yuan, the risk points cannot be completely resolved. In this case, the managers can refer to the roadmap and give priority to the top-ranking sub-events (i.e., G_1 and below).

4. Conclusions

This study developed an integrated framework for designing methods for environmental risk mitigation in chemical plants. Our method considered the countermeasure cost and critical values and adopted BWM to conduct a quantitative analysis of the risk points of a chemical plant. A pharmaceutical intermediate plant was used as the case study to demonstrate the functionality of the integrated framework.

The proposed framework only considers the resolution results of the countermeasure costs and critical values. The entire implementation durations to resolve sub-points is not fully considered. Additionally, we intend to further improve our method by considering the effects of various factors on risk reduction in chemical plants.

References

Abrahamsen, E.B., Abrahamsen, H.B., Milazzo, M.F., Selvik, J.T., 2018. Using the ALARP principle for safety management in the energy production sector of chemical industry. Reliability Engineering & System Safety 169, 160-165.

Ciarapica, F., Bevilacqua, M., Antomarioni, S., 2019. An approach based on association rules and social network analysis for managing environmental risk: A case study from a process industry. Process Safety and Environmental Protection 128, 50-64.

Gupta, P., Anand, S., Gupta, H., 2017. Developing a roadmap to overcome barriers to energy efficiency in buildings using best worst method. Sustainable Cities and Society 31, 244-259.

Jung, S., Ng, D., Lee, J.-H., Vazquez-Roman, R., Mannan, M.S., 2010. An approach for risk reduction (methodology) based on optimizing the facility layout and siting in toxic gas release scenarios. Journal of Loss Prevention in the Process Industries 23(1), 139-148.

Malek, J., Desai, T.N., 2019. Prioritization of sustainable manufacturing barriers using Best Worst Method. Journal of Cleaner Production 226, 589-600.

Rezaei, J., 2015. Best-worst multi-criteria decision-making method. Omega 53, 49-57.

Rezaei, J., Nispeling, T., Sarkis, J., Tavasszy, L., 2016. A supplier selection life cycle approach integrating traditional and environmental criteria using the best worst method. Journal of Cleaner Production 135, 577-588.

Setyono, R.P., Sarno, R., 2018. Vendor Track Record Selection Using Best Worst Method, International Seminar on Application for Technology of Information and Communication (iSemantic).

Tan, R.R., Aziz, M.K.A., Ng, D.K.S., Foo, D.C.Y., Lam, H.L., 2016. Pinch analysis-based approach to industrial safety risk and environmental management. Clean Technologies and Environmental Policy 18(7), 2107-2117.

Wang, F., Gao, Y., Dong, W., Li, Z., Jia, X., Tan, R.R., 2017. Segmented pinch analysis for environmental risk management. Resources, Conservation and Recycling 122, 353-361.

Wikimili, 2019. 2019 Xiangshui chemical plant explosion. Available at: https://wikimili.com/en/2019_Xiangshui_chemical_plant_explosion. Accessed at: 09.09.2019