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System-Theory Accident Models and Processes for Fire Risk Management of Chemical Plants

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A fire risk analysis was conducted to evaluate and manage the potential for accidents in the petrochemical industry. From the perspective of systems and control theory, this study proposes a fire risk assessment and management method for chemical plants based on system-theory accident models and processes. An integrated framework was proposed to assess and manage fire risk in chemical plants. Hazard and operability analyses were conducted to identify the deviations and contributing factors leading to fires in a chemical plant. For fire risk points, a hierarchical control structure model of the system production process was integrated with the internal production and external safety management interactive feedback unit to clarify the safety constraints and controls. Chemical plant operation scenarios were developed to focus on coordination and feedback between multiple organizations in the system. A decision-making trial and evaluation laboratory (DEMATEL) and interpretative structural modeling (ISM) were combined with an analysis of constraint defects. A case study of a fatty alcohol polyoxyethylene ether plant was conducted. The results show that the DEMATEL–ISM model describes the potential cross-level control process and can comprehensively analyze the relationship between contributing factors to improve the system's overall safety and prevent accidents.

1. Introduction

Chemical plants are prone to fire accidents, with disastrous consequences. To improve process safety, safety analysis must be conducted to identify fire hazards in chemical plants, assess the risk level of the production system, and provide a basis for the development of risk control measures. Accidents are analyzed to formulate targeted measures to ensure system safety. Shirali et al. (2012) presented the resilience engineering theory to identify constraints and safety barriers in maintenance management systems to achieve high reliability and resilience in plants. Koo et al. (2021) used AcciMap and the functional resonance analysis method to analyze explosion accidents in Korean chemical plants and proposed policy solutions for accident prevention. Barozzi et al. (2022) compared a risk analysis on a chemical plant subject of modifications performed with safety engineering tools, and the study showed that the Recursive Operability Analysis (ROA) is more effective in a risk assessment update. El-Arkam et al. (2023) considered a System-theory accident model and processes (STAMP) for studying High-Density Poly-Ethylene (HDPE) reactors to improve safety and better manage risk.
STAMP refers to accident models of complex systems (Leveson, 2004). The core concept is that accidents are the result of interactions between different elements in a complex system; the absence of control actions imposing constraints on these interactions leads to accidents. The purpose is to maintain the controlled object within a safe range. STAMP is used in the chemical industry to analyze oil transportation pipeline explosion accidents and ensure the safe operation of natural gas storage tanks. However, the STAMP model lacks defects in the cross-level control process. It is unable to determine the relative intensity of accident-influencing factors to highlight key points in formulating preventive measures. Decision-Making Trial and Evaluation Laboratory-Interpretive Structural Model (DEMATEL-ISM) is to identify causal relationships and hierarchies between elements in a complex system (Zhou et al., 2006). This study introduces DEMATEL-ISM based on the STAMP model to address this defect. DEMATEL was used to visualize complex interrelationships between criteria and identify key influencing factors. ISM was used to represent ambiguous systems with intuitive

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structural relations (Chauhan et al., 2018), facilitating objective analysis of complex problems. Thus, DEMATEL-ISM converts a complex chemical production system into a multilevel hierarchical system model. Before modeling a chemical production system, the hazard and operability analysis (HAZOP) method is used to identify comprehensive risks.

2. Methods

2.1 STAMP model

The STAMP model contains three basic structural units: safety constraints, a hierarchical control structure, and a process model. The safety system is divided into multiple layers; the upper and lower layers are linked. The upper system imposes constraints on the lower system and controls its behavior. Constraints are passed down layer by layer; the lower system provides feedback implementation results to the upper system. The process model is the main component of the STAMP model and represents the interaction between control levels.
For a chemical plant production system, the STAMP hierarchical control structure describes system behavior; it can be divided into four levels: physical, basic, management, and government. (1) The physical layer includes safety facilities and interlocking devices related to production equipment in the plant and installed emergency and firefighting facilities. The basic safety facilities of a plant are the first line of defense to ensure safe production. (2) The basic level is divided into team leader and operator. The production and safety equipment are directly controlled at the physical layer to ensure production system safety. (3) The management level ensures the normal operation of the system. It imposes constraints at the grassroots level through management, including technical and safety guidance, formulation of production plans, formulation of safety objectives, popularization of safety training, and safety inspection. (4) The government level includes two units: relevant government agencies and parks. Government agencies guide the organizational and departmental layers in their work, perform government functions, provide timely intervention in chemical production projects, conduct strict safety reviews, and implement the main responsibilities of the company. A chemical park is a key link between the government and the plant; the main constraint in the hierarchy is the management of the company.

2.2 HAZOP analysis method

HAZOP analysis is a highly specialized, structured, and systematic qualitative evaluation method. Conducted by a multidisciplinary team in a series of discussion sessions, hazard scenario analysis identifies deviations from the design intent to identify potential hazards and make recommendations (Guo et al., 2015). A HAZOP analysis divides the plant into sections (nodes) to determine deviations from the design intent. A deviation is a combination of process parameters and guide words. A 'brainstorming' risk assessment method proposes more effective protection measures. Preparation for HAZOP analysis includes assembling the analysis team, collecting analysis data, determining the analysis scope, defining the nodes, and identifying deviations. This study focuses on a production system for fatty alcohol polyoxyethylene ether, which includes temperature, pressure, and flow; the guide words are 'none', 'more', and 'less'. The HAZOP analysis team includes instrument engineers (team leaders), chemical engineers, safety engineers, chemical process engineers, factory directors, safety directors, central control room operators, and recorders.

2.3 DEMATEL-ISM model

DEMATEL can be used to visualize complex relationships between standards and identify key influencing factors. The ISM can decompose a complex system into multiple subsystem factors, use expert experience and knowledge to determine the relationship between any two factors and present the relationship between each factor hierarchically (Zhou et al., 2019). DEMATEL and ISM are combined to determine the causal relationship and hierarchical structure between elements in a complex system and determine the most important constraints that affect risk (Chen, 2021) for systematic analysis of chemical plant production system safety risk factors.

2.3.1 Construction of DEMATEL model

(1) Establish direct influence matrix X and comprehensive influence matrix T
This study used 0, 1, 2, and 3 scales to determine the relationships between the factors through expert evaluation. As the degree of influence increases (0 = influence, 1 = weak influence, 2 = moderate influence, 3 = strong influence), each factor on the main diagonal is denoted as 0, and the initialization direct-relation influence matrix X is obtained as Eq(1).

$$X=\begin{bmatrix} 0 & x_{12} & \cdots & x_{1n} \\ x_{21} & 0 & \cdots & x_{2n} \\ \vdots & & \ddots & \vdots \\ x_{n1} & x_{2n} & \cdots & 0 \end{bmatrix} \tag{1}$$

After taking the maximum value of the row sum as the normalized cardinality, the transformation matrix X becomes the normalized direct-relation matrix N shown as Eq(2).

$$N=\frac{X}{max_{1\leq i\leq n}\sum_{j=1}^{n}x_{ij}} \quad (2)$$

Calculate the comprehensive influence matrix T shown as Eq(3).

$$T=N(I-N)^{-1} \quad (3)$$

(2) Calculate the influence degree, influenced degree, cause degree, and central degree
The influence degree and influenced degree are calculated as shown in Eq(4) and Eq(5). Influence degree is the sum of the elements in each row of T and the influence of the factors corresponding to that row on other factors; Influenced degree is the sum of the elements in each column of T and the degree to which the factors corresponding to this column are influenced by other factors. Eq(6) and Eq(7) show the cause degree and central degree, respectively. Cause degree is the function of a factor in the system and is determined by calculating the difference between the influence degree and the influenced degree of the factor. If it is positive, the factor has a great influence on other factors in the system and is a causal factor; If it is negative, the factor is greatly influenced by other factors in the system and is a result factor; Central degree is the importance of a factor in the system is determined by calculating the sum of its influence degree and influenced degree. The larger the central degree, the more important it is in the system.

$$F_i=(f_i)_{n\times 1}=\sum_{i=1}^{n}t_{ij} \quad (4)$$

$$C_i=(c_i)_{1\times n}=\sum_{j=1}^{n}t_{ij} \quad (5)$$

$$E_i=F_i-C_i \quad (6)$$

$$M_i=F_i+C_i \quad (7)$$

2.3.2 Construction of ISM model

Because the DEMATEL method does not consider the influence of the factors on themselves, the unit matrix I is summed to form the overall influence relationship matrix H shown as Eq(8).

$$H=T+I \quad (8)$$

To obtain the reachability matrix, it is necessary to introduce thresholds λ to eliminate relationships with a small degree of influence and simplify the system structure shown in Eq(9).

$$K=k_{ij}\begin{cases}=1,\ h_{ij}\geq\lambda\\ =0,\ h_{ij}\leq\lambda\end{cases} \quad (9)$$

From the reachability matrix, we obtain the reachability, antecedent, and intersection sets. The reachable set is the set of all factors, with element 1 in a row corresponding to the reachability matrix denoted by $P(X_i)$ shown as Eq(10). The prior set is the set of all factors with element 1 in a column of the corresponding reachability matrix, denoted by $Q(X_i)$ shown as Eq(11).

$$P(X_i)=\{X_j/X_j\in X,k_{ij}=1\} \quad (10)$$

$$Q(X_i)=\{X_j/X_j\in X,k_{ji}=1\} \quad (11)$$

The ISM hierarchy of risk factors is obtained by dividing the sets of different levels of risk factors according to the cause–effect priority algorithm shown as Eq(12).

$$J(X_i)=P(X_i)\cap Q(X_i) \quad (12)$$

The factors corresponding to $J(X_i)$ can be reached by some factors but not by others. Thus, all factors that satisfy

$P(X_i)=J(X_i)$ are taken as the first layer of the factor sets, and the factors of the first layer in the reachability and antecedent sets are temporarily deleted. These steps are continued in the remaining matrix until the hierarchical division of all factors in the system is completed to obtain the ISM level of each factor.

3. Case study

A fatty alcohol polyoxyethylene ether plant was considered as a case study to analyze fire risk management. The plant produces polyoxyethylene surfactants through the oligomerization of ethylene oxide and active hydrogen-containing compounds (Amaral et al., 2011). The plant operated safely (without accidents) during the trial period.

3.1 Identifying system fire risk and interference based on HAZOP

The scope of the HAZOP analysis was the fatty alcohol polyoxyethylene ether production system, which included the entire fatty alcohol polyoxyethylene ether production process. The production system was divided into five nodes: pre-treatment tank, main reactor, post-treatment tank, ethylene oxide feed unit, and storage tank. Deviation analysis was conducted to determine the risk indicated by the guide words. The main fire hazards in the plant were concentrated in the main reactor, the ethylene oxide feeding system connected to the main reactor, and the ethylene oxide storage system, based on HAZOP analysis. After determining the fire risk factors in the plant, a control process model and related safety constraints were established around the fire risk points.

3.2 Establishment of Safety Control Structure in Chemical Plant

To systematically analyze the risk factors for chemical plant fires, based on the STAMP model and actual chemical plant conditions, we established a safety control structure for fatty alcohol polyoxyethylene ether chemical plants, as shown in Figure 1.

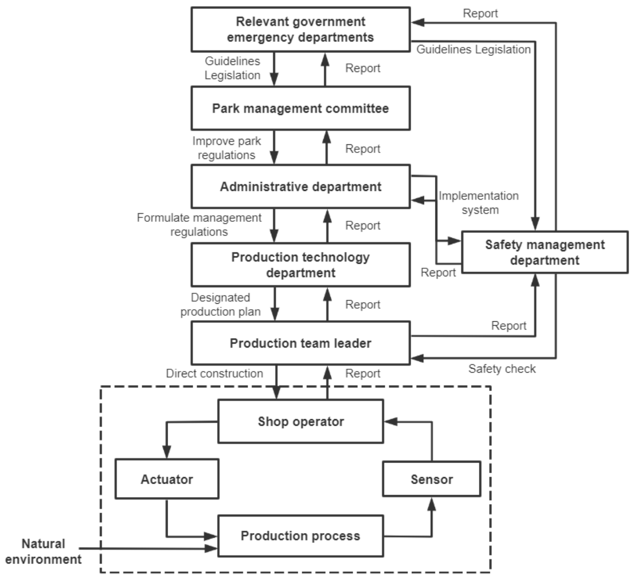

Figure 1: Chemical plant safety control structure

3.3 Analysis of Safety Constraints in Chemical Plants

According to the safety control structure diagram constructed for chemical plant operation scenarios, implementation of the fire risk source-related control function was determined using HAZOP analysis. Starting at the physical, basic, management, and government levels, possible constraint defects in the chemical plant were analyzed; 23 main constraint defects were identified, as presented in Table 2. The accident simulation performance was determined.

3.4 Impact of chemical plant fire accidents based on DEMATEL–ISM model

Based on the STAMP model, 23 factors contributing to chemical plant fire accidents were identified. Several experts were invited to score the degree of influence of the contributing factors. Eqs(1)-(3) were used to calculate the comprehensive influence relation matrix T; Eqs(4)-(7) were used to obtain the centrality and causality of each safety constraint to draw a centrality–cause graph, as shown in Figure 2. The reachability matrix K was obtained using Eq(8) and Eq(9), with an introduction threshold λ=0.1. According to Eqs(10)-(12), the reachable matrix K was divided into different levels. A nine-level recursive hierarchical model of system constraint defects was constructed. Regarding the values of the elements in the reachability matrix K, the causal factors were connected by arrows to produce the ISM hierarchy diagram with interactions shown in Figure 2.

Table 2: Defect of safety constrain in plant

System level	Control structure	Constraint defect
physical level	Production equipment	Production equipment failure x1
		Failure prevention facilities x2
		Failure of control accident facilities x3
		Failure of fire-fighting and emergency facilities x4
	Environment	Environmental effect x5
basic level	Operator	Incorrect operation x6
		Fatigue operation x7
	Foreman	Lack of team education management x8
		Insufficient process preparation before production x9
		Insufficient equipment maintenance x10
		Wrong coordination work x11
management level	Technical Department	Not familiar with the production process x12
		Lack of technical guidance for the team x13
		Make a wrong production plan x14
	Safety Department	Lack of safety system x15
		Insufficient safety training x16
		Invalid safety check x17
		Lack of emergency management measures x18
	Administration	Improper implementation of system x19
		Miscoordination x20
government level	Park	Negligence of supervision and inspection x21
		Related facilities in the park are insufficient x22
	Government	Policy formulation is not perfect x23

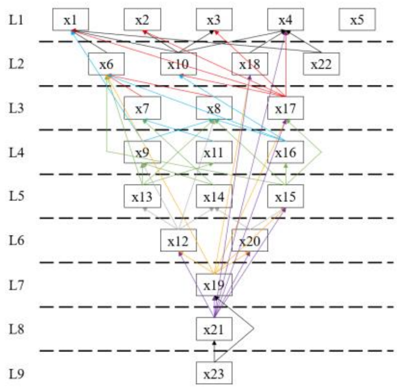

Figure 2: Structure level of ISM

In this system, the main causal factors were the dereliction of duty in supervision and inspection (x21), improper implementation of the system (x19), and imperfect formulation of policy (x23), which greatly affected other factors, including production equipment failure (x1), fire facility failure (x4), incorrect operation (x6), and lack of team education management (x8), affecting the safety of the entire system. In future safety management, the safety level of a factory can be improved by strengthening plant supervision and implementing policies at all levels. Combination and comparative analysis of constraint defects at different levels obtained from the ISM hierarchy diagram and STAMP model show that the meaning of each element level is consistent with the constraint defects at each level in the STAMP model, as shown in Figure 2. The feasibility of the STAMP model is demonstrated. The ISM model can scientifically compensate for the lack of cross-level control processes in STAMP. The overall safety of the system can be improved, and accidents can be prevented by implementing government laws, regulations, and policies.

4. Conclusions

Chemical plants can be affected by uncertainties in the production process, leading to failures that are likely to have serious consequences. Chemical companies ensure safety during their operations and production processes. In this study, based on the STAMP system accident theory model, HAZOP was used to analyze and identify 11 deviations and causes of fire accidents in the system. Using the basic information and operation steps of the DEMATEL–ISM method, a multi-level hierarchical model of causal factors was established. The results show that a combination of the STAMP and DEMATEL–ISM models can overcome the deficiencies of traditional STAMP model analysis and the limitation of any two-factor relationship classification in the traditional ISM model to analyze further the logical relationship between accident risk factors and impact intensity. This paper still has some limitations. Since many constraints and defects are determined, and the pertinence is not strong, further studies can be carried out on a certain category of factors such as human errors, material, environment, technology, and management. STAMP and enterprise-level models can also be combined to establish and simulate the integrated model to make the system monitoring and risk assessment more automatic and intelligent.

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