



Identification and Prioritization of Factors Affecting the Location of Safe Shelters and Emergency Evacuation Routes in Process Industries Using the Analytic Hierarchy Process

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ABSTRACT

Process industries, due to their operational nature and the presence of hazardous chemicals, are constantly exposed to extensive risks such as fire, explosion, and the release of toxic substances. Under such circumstances, the establishment of safe shelters and the designation of efficient emergency evacuation routes, as two fundamental components of the crisis management system, play a vital role in reducing human casualties and enhancing industrial resilience. The present study was conducted with the aim of identifying and prioritizing the factors affecting the location of safe shelters and the determination of emergency evacuation routes in process industries in scenarios such as the release of toxic substances using the Analytic Hierarchy Process approach. In this study, a review of scientific sources was first conducted to extract the key criteria influencing the location of safe shelters and the determination of emergency evacuation routes. Subsequently, utilizing an expert panel method (comprising 13 faculty members specializing in industrial safety and crisis management), the extracted criteria were validated and supplemented. The data collection instrument was a pairwise comparison questionnaire based on Saaty's scale (1 to 9). The final weights of the criteria were calculated using the AHP method, and the consistency of the judgments was confirmed through the calculation of the inconsistency ratio. The findings indicated that in the location of safe shelters, the criteria of "minimum exposure to hazardous materials" (C1) and "distance from the hazard source" (C2), with equal weights of 0.16, possess the highest priority. The criteria of "access to safe routes" (C3) and "optimal evacuation time" (C4) were ranked subsequently. Among the factors affecting the determination of emergency evacuation routes, the criterion of "susceptibility to the accident" (C3) with a weight of 0.22 had the highest priority, followed by "population distribution at the site" (C1) and "population density along the routes" (C2). Prioritizing the criteria of distance from hazard sources and route safety in the design of emergency management systems can effectively contribute to reducing human casualties, preventing widespread consequences, and enhancing the resilience of process industries. The findings of this study can serve as a foundation for developing location standards, revising comprehensive emergency response plans, and improving the level of safety in high-risk industrial units.

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Introduction

Process industries, due to their operational nature and the presence of hazardous chemicals, are inherently exposed to extensive risks including fire, explosion, and the release of toxic substances. The occurrence of accidents in these industries can result in catastrophic consequences, not only in terms of human casualties and financial losses but also with irreversible impacts on surrounding communities and the environment. When primary accidents occur in chemical facilities, the chain-like nature and physicochemical interactions between adjacent units create the potential for propagation to neighboring equipment, potentially leading to the "domino effect" phenomenon, which exacerbates the scale of the disaster.

The establishment of safe shelters and the designation of efficient emergency evacuation routes constitute two fundamental components of crisis management systems, playing a vital role in reducing human casualties and enhancing industrial resilience. Rescue centers in chemical industrial complexes serve as key operational infrastructure components within emergency management systems, responsible for providing and distributing emergency resources, personal protective equipment, and sheltering exposed individuals in a timely manner. Safe shelters serve a dual function: providing temporary accommodation for affected populations who lack alternative safe locations and offering specialized medical care for those requiring immediate attention. These shelters must possess adequate physical space to meet basic survival needs and primary healthcare services.

Emergency evacuation, defined as the purposeful relocation of individuals from identified hazard zones toward safe locations within the shortest possible time and with maximum reliability, represents a critical pillar of crisis response systems. Based on available warning time, emergency evacuation scenarios can be broadly classified into precautionary operations, where sufficient warning time enables pre-assessment and planning, and life-saving operations, characterized by limited or absent warning, necessitating immediate rescue of injured individuals and clearing of access routes.

Due to the inherent diversity of evacuation scenarios and their susceptibility to multiple and sometimes conflicting factors, selecting the best operational strategy requires simultaneous assessment of numerous indicators. Safety experts in process industries possess different perspectives regarding safety system evaluation indicators, naturally leading to different levels of importance for each indicator. Multiple-Criteria Decision-Making methods have emerged as efficient approaches for addressing these complexities. Among various MCDM methods, the Analytic Hierarchy Process, first introduced by Saaty in 1980, has become one of the most practical tools for integrating expert opinions and evaluating scores. Despite the breadth of studies in crisis management, limited research has specifically addressed the identification and prioritization of factors affecting the location of safe shelters and emergency evacuation routes in process industries using MCDM techniques. Therefore, this study was designed with the objective of identifying and prioritizing these factors using the Analytic Hierarchy Process approach.

Method

This study employed a systematic multi-stage methodology to identify and prioritize key factors affecting the location of safe shelters and emergency evacuation routes in process industries. Initially, a comprehensive review of credible scientific literature and previous studies in crisis management, process safety, and emergency facility location was conducted. Based on the findings, a set of criteria were extracted covering various aspects of the subject. The identified dimensions for ranking the location of safe shelters included: C1 (minimum exposure to hazardous materials), C2 (distance from hazard source), C3 (access to safe routes), C4 (optimal evacuation time), C5 (environmental and climatic requirements), C6 (potential for accident impact), C7 (easy access), C8 (emergency facilities and infrastructure), and C9 (minimum access time). Factors identified as effective in determining evacuation routes included: C1 (population distribution at the site), C2 (population density along routes), C3 (susceptibility to the accident), C4 (maximum route capacity), C5 (time from route to safe assembly point), and C6 (exit locations).

An expert panel comprising 13 faculty members specializing in occupational health and safety and crisis management was formed. All participants held doctoral degrees, with ages ranging from 31 to over 45 years and work experience spanning 1 to over 15 years, ensuring diversity of perspectives. A pairwise comparison questionnaire based on Saaty's standard scale (1 to 9) was designed to measure the relative

importance of each factor. The Consistency Ratio was calculated to assess inconsistency in judgments, with values less than 0.1 considered acceptable. The final weights of the criteria were calculated using the AHP method based on the pairwise comparison matrices.

Results

The results revealed distinct prioritization patterns for safe shelter location compared to emergency evacuation route criteria. For safe shelter location, the criteria of "minimum exposure to hazardous materials" (C1) and "distance from hazard source" (C2), with equal weights of 0.16, demonstrated the highest priority. The criterion of "access to safe routes" (C3) with a weight of 0.15 ranked third, followed by "optimal evacuation time" (C4) with a weight of 0.12 in fourth position. These four criteria collectively accounted for the highest weights, indicating their dominant influence in the decision-making process. In contrast, criteria including environmental and climatic requirements (0.09), potential for accident impact (0.11), easy access (0.09), emergency facilities and infrastructure (0.06), and minimum access time (0.07) exhibited lower priority.

For emergency evacuation route determination, the criterion of "susceptibility to the accident" (C3) with a weight of 0.22 demonstrated the highest priority. The criteria of "population distribution at the site" (C1) and "population density along routes" (C2) ranked second and third with weights of 0.20 and 0.19 respectively. These three criteria collectively received the highest weights, demonstrating their dominant influence in evacuation route design. The Consistency Ratio for all participants' judgments was confirmed within the acceptable range (less than 0.1), indicating internal consistency and appropriate reliability of the pairwise comparisons conducted.

Conclusions

The present study successfully identified and prioritized factors affecting the location of safe shelters and emergency evacuation routes in process industries using the Analytic Hierarchy Process approach. The findings revealed that for safe shelter location, the criteria of "minimum exposure to hazardous materials" and "distance from hazard sources" possess the highest priority, followed by "access to safe routes" and "optimal evacuation time," indicating the critical importance of distancing from hazards and speed of access in shelter design. Conversely, in determining emergency evacuation routes, the criterion of "susceptibility to the accident" demonstrates the highest importance, followed by "population distribution at the site" and "population density along routes," indicating the necessity of prioritizing route safety against process hazards.

Based on these findings, safety engineers should calculate minimum safe distances based on consequence modeling of critical scenarios and establish shelters outside hazard radii. In evacuation route design, network nodes exposed to domino effects should be eliminated and alternative routes with minimum hazard exposure should be determined using route optimization algorithms. Evacuation route capacity should be calculated based on maximum floating and working population per shift, and potential bottlenecks should be eliminated to optimize evacuation time. In revising comprehensive emergency response plans, higher-weight criteria should be defined as key performance indicators and compliance of existing shelters and routes should be monitored. Ultimately, prioritizing distance from hazard sources and route safety criteria in emergency management system design can effectively contribute to reducing human casualties, preventing consequences arising from domino effects, and enhancing resilience of process industries, providing an effective operational framework for safety engineers and crisis managers toward improving safety levels in high-risk industrial units.

منابع خطر" با وزن مساوی ۰,۱۶, بالاترین اولویت را دارند. در رتبه‌های بعدی، معیارهای "دسترسی به مسیرهای ایمن" و "زمان بهینه تخلیه" قرار می‌گیرند که بیانگر اهمیت حیاتی فاصله‌گیری از مخاطرات و سرعت دسترسی در طراحی پناهگاه‌هاست. در مقابل، در تعیین مسیرهای تخلیه اضطراری، معیار "تأثیرپذیری از حادثه" با وزن ۰,۲۲، بیشترین اهمیت را داشته و معیارهای "توزیع جمعیت در محل" و "چگالی جمعیت در مسیرها" در اولویت‌های بعدی قرار گرفته‌اند که نشان دهنده لزوم اولویت‌دهی به ایمنی مسیر در برابر مخاطرات فرایندی است. بر اساس این یافته‌ها، مهندسان ایمنی می‌بایست در مکان‌یابی پناهگاه‌ها، حداقل فاصله ایمن را بر اساس مدل‌سازی پیامد سناریوهای بحرانی نظیر انفجار و انتشار گازهای سمی محاسبه و پناهگاه‌ها را خارج از شعاع خطر استقرار دهند. همچنین، در طراحی مسیرهای تخلیه، گره‌های شبکه‌ای که در معرض اثر دومینو قرار دارند، باید از شبکه حذف و مسیرهای جایگزین با کمترین میزان مواجهه با مخاطرات با استفاده از الگوریتم‌های بهینه‌سازی مسیر تعیین گردند. ظرفیت مسیرهای تخلیه نیز می‌بایست بر اساس حداکثر جمعیت شناور و شاغل در هر شیفت محاسبه شده و گلوگاه‌های احتمالی از طریق افزایش پهنای مسیر یا ایجاد مسیرهای موقت برطرف شوند تا زمان تخلیه بهینه گردد. در بازنگری طرح‌های جامع پاسخ به شرایط اضطرار، معیارهای با وزن بالاتر به‌عنوان شاخص‌های کلیدی عملکرد تعریف شده و میزان انطباق پناهگاه‌ها و مسیرهای موجود با این شاخص‌ها، پایش گردد. برای واحدهای در حال احداث، نتایج این مطالعه می‌تواند در مرحله طراحی مفهومی به عنوان چک لیست الزامات ایمنی مورد استفاده قرار گیرد تا از بروز هزینه‌های اصلاحی در مراحل بعدی پیشگیری شود. در نهایت، اولویت‌دهی به معیارهای فاصله از منابع خطر و ایمنی مسیر در طراحی سیستم‌های مدیریت اضطراری، می‌تواند نقش مؤثری در کاهش تلفات انسانی، جلوگیری از پیامدهای ناشی از اثرات دومینو و افزایش صنایع فرایندی ایفا کند و چارچوب عملیاتی این مطالعه، ابزاری کارآمد برای مهندسان ایمنی و مدیران بحران در راستای ارتقاء سطح ایمنی واحدهای صنعتی با ریسک بالا فراهم می‌آورد.

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