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Original Article

Multi-Criteria Decision Approach for Evaluating Fire Safety Strategies in Hazardous Material Intermodal Transfers

Pradeep Piplotiya[1], Vijay Shankul[2]

[1,2]*Department of Fire Technology & Safety Engineering, IPS Academy Institute of Engineering and Science, A.B. Road, Rajendra Nagar, Indore, Madhya Pradesh, India.*

[1]*Corresponding Author : pradeeppiplotiya143@gmail.com*

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Abstract *- Current scenario gives a major challenge that arises during fire safety frameworks, which is the transportation and transfer of hazardous materials across intermodal facilities transparent. This research represents an integrated Multi-Criteria Decision-Making (MCDM) approach for the evaluation and selection of fire safety strategies in hazardous materials. The study majorily focuses on the Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution TOPSIS), and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHE) methodology to establish an effective decision support framework for safety. In fact, the identification of twelve primary fire safety evaluation it organized across four hierarchical categories: facility infrastructure, operational protocols, emergency response capability, and regulatory compliance. The evaluation enables the terminal managers and safety engineers to prioritize fire safety interventions with empirical accuracy. The application of blurred logic extensions to the AHP framework recognizes the uncertainty inherent in expert judgment and the real-world operational. Comparative analysis across the different levels of fire safety strategy alternatives determines that integrated MCDM approaches are superior in terms of ranking consistency and actionable insights related to traditional single-criterion assessment methods. The findings underscore the efficiency of systematic, multidimensional evaluation frameworks in hazardous material transfer operations where catastrophic events relate to the high consequences extended across the human safety, environmental impact, and operational continuity dimensions.*

Keywords *- AHP, Fire Safety, Hazardous Material, Intermodal Transfer, Promethee, Topsis.*

1. Introduction

Over the past two decades, the movement of hazardous materials through intermodal logistics systems has rapidly increased, mostly because of the expansion of global trade and the globalization of manufacturing. It is estimated that more than four million intermodal containers transport both hazardous and non-hazardous goods each year across maritime, rail, and road networks around the world. While this growth plays an important role in sustaining the development of modern supply chains, it also brings a rise in operational risks, particularly during the transfer of activities at intermodal terminals. These environments factors are complex, as materials are transferred between transportation modes within confined spaces where containers are often stored and handled at close proximity levels. Such conditions can instantly identify the impact of fire incidents whenever they occur. Although, the studies in Fire engineering has identified various key challenges related to hazardous material incidents in these settings.

These preferably include the difficulty in identifying hazardous contents within stacked containers, limited accessibility for emergency response teams, and the potential risks arising from the unintended mixing of incompatible chemical substances in an inappropriate manner during handling operations. Noureddine et. Research further highlights that these risks are multidimensional and cannot be addressed or protected through simplified or single-factor methods. To forecast these challenges, there should be a development of effective fire safety strategies for intermodal terminals, which requires a comprehensive and integrated approach to overcome these. This involves not only the technical facility design, but also the robustness of operational procedures within the readiness of emergency response systems, and adherence to important regulatory frameworks. Traditional approaches in hazardous material operations have mostly relied on qualitative risk matrices, past incident data, and established regulatory guidelines and principles. Although these methods provide a useful starting point for ensuring the safety of hazardous materials, they often fall short in terminal environments where various fire safety strategies need to be compared with different criterion methods. Research on Multi-Criteria Decision-Making (MCDM) in hazardous material transport and storage shows that well-structured evaluation methods can also improve decision quality to ensure safety. These approaches allow different or various types of factors to be considered together while also incorporating expert opinions, whether their judgments, which are often uncertain in nature. In this context, the present study aims to address the gap between the practical challenges of selecting fire safety strategies and the potential of modern decision-making approaches. An integrated framework is also established that uses the Analytic Hierarchy Process (AHP) to determine the importance of criteria, along with TOPSIS and PROMETHEE methods to rank the available techniques sequentially. To check the uncertainty associated with expert judgment. Fuzzy set theory is incorporated into the framework. The evaluation is based on four key categories: facility infrastructure, operational procedures, emergency response capability, and regulatory compliance. Despite the increasing emphasis of research on hazardous material transportation, fire risk assessment, and multi-criteria decision-making approaches, various important challenges remain unresolved. Most upcoming studies primarily focus on individual fire safety factors, regulatory compliance, or the application of a single decision-making method. Although Limited attention has been given to the integrated evaluation of fire safety methods in hazardous material intermodal transfer operations by combining the multiple MCDM techniques within a unified decision-support framework app roach Furthermore, comparing the validation of alternative fire safety strategies using other complementary ranking methods such as AHP, TOPSIS, and PROMETHEE has further gained limited attention in previous studies. Therefore, there is a need for an inclusive trending growth framework that systematically evaluates, prioritizes, and validates fire safety strategies to support a more reliable and effective decision-making approach in hazardous material intermodal transfer facilities. In this context, the current study introduces an integrated multi-criteria decision-making framework that further combines the AHP, TOPSIS, and PROMETHEE to evaluate and prioritize the fire safety strategies in hazardous material intermodal transfer operations. The introduced framework determines the major importance of the fire safety criteria using AHP, ranks alternative strategies using TOPSIS and PROMETHEE, and performs the sensitivity analysis to evaluate the robustness of the obtained rankings. The proposed approach gives a structured decision-support framework to improve the fire safety planning and resource allocation in hazardous material logistics. The introduced framework differs from existing research by integrating three well-established multi-criteria decision-making methods, namely AHP, TOPSIS, and PROMETHEE, within a single framework for evaluating the fire safety strategies in hazardous material intermodal transfer operations. While earlier studies have mainly applied these techniques individually or focused on specific fire safety aspects, the present study merges them to provide a more comprehensive evaluation, an inclusive and reliable ranking of alternative fire safety strategies. The inclusion of sensitivity analysis further improves confidence in obtaining the results and enhances the practical applicability of the proposed framework.

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Table 1. Evolution of Hazardous Materials

Time Period	Development Focus	Major Hazardous Material	Key Observation	Reference
Before the industrial age(Before 1800)	Use of harmful natural substances in early times	Arsenic, Mercury, Lead	People are not aware of its Harmful effect.	[1]
During the industrial Revolution (1800-1900)	Growth of industries	Coal, sulfur compounds, industrial chemicals	Pollution increased significantly, which affected worker Who get exposed to harmful substances.	[15]
After The Second World War (1945-1970)	Growth of chemical industries	Toxic gases, explosives	Used a lot in wars and industries, which caused serious harm.	[12]
After the war years (1945–1970)	Increase in the use of nuclear and artificial chemicals	Radioactive materials, pesticides	Increased pollution can cause disease, leading to health concerns.	[1, 2]
Environmental Awareness Era (1970–2000)	Regulation & control	Industrial waste, plastics	Laws and safety standards establishment.	[2, 16]
Modern Era (2000–Present	Advanced & emerging hazards	E-waste, biohazards, nano materials	Global concern, strict rules and regulations.	[15, 16]

2. Literature Review

2.1. Multi-Criteria Decision-Making Methodological Foundation

MCDM represents a structured Family of analytical approaches which designed to address complex decision problems. [7]. The foundational literature in MCDM recognises that single-criterion. optimization subsequently captures real-world complexity where decisions are fundamentally involved in trade-offs. This recognition has ensured substantial MCDM methodological development across multiple application domains, including environmental management, facility sitting, supply chain optimization, and safety systems design [8]. (AHP), developed by Saaty (1977, 1980), remains among the most extensively applied MCDM techniques [9]. The AHP methodology reduces complex decision problems into hierarchical structures, and the primary objective is subsequently subdivided into constituent criteria and sub-criteria levels. Pairwise comparison matrices establish relative weights among criteria at each hierarchical level through elicitation of expert judgment opinions. Consistency ratio verifies the logical coherence of comparative judgments, thereby reducing the influence of irrational or contradictory expert opinions. Moreover, the mathematical foundation of AHP enables the transformation of qualitative expert opinion into quantitative weighting schemes to preserve the fundamental decision structure [9]. Contemporary applications of AHP demonstrate particular utility in hazardous material logistics contexts. Watchara Sattayaprasert and colleagues applied AHP methodology to magnify risk-based routing networks for hazardous material transportation, establishing that hierarchical decomposition of route selection criteria improved network optimization related to single-risk-dimension approaches [10]. The incorporation of fuzzy logic theory into AHP frameworks, termed as Fuzzy AHP (FAHP), summons appropriate measurement in expert judgment opinions through representation of comparative assessments as triangular or trapezoidal fuzzy numbers rather than discrete point estimates [11]. This methodological extension guarantees valuable options in operational safety contexts where expert confidence reflects genuine epistemic uncertainty regarding comparative criterion importance.

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) represents, according to fundamentally different mathematical principles, a departure from AHP-derived weighting schemes. TOPSIS analysis multiple options by calculating geometric distances between each alternative's characteristic profile and both the ideal and negative-ideal solution points within the criterion space [12]. These alternatives were subsequently ranked according to their relative proximity to the ideal solution. TOPSIS have some advantages, which include computational transparency regarding distance calculations and interpretation of results for end-users who may not be aware of specialized MCDM training. Furthermore Research comparing TOPSIS performance across diverse application domains indicates particular robustness when decision problems involve separate alternatives with quantifiable performance indicators [14].

The Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) represents an outranking methodology distinct from distance-based approaches employed by TOPSIS. PROMETHEE contains pairwise preference to relations among alternatives through the application of preference functions established by decision-makers for each criterion (15). These preference functions organise the decision-maker's subjective preferences regarding the strength with which one alternative dominates another criterion dimension. PROMETHEE subsequently recognises pairwise preferences to establish overall alternative rankings. In this way, the methodological Flexibility of PROMETHEE in accommodating criterion-specific Preference function defines valuable in complex operational contexts where the relationship between. Criterion performance and decision-maker preference vary subsequently across different criteria [17].

2.2. Fire Safety Assessment in Hazardous Material operation

Fire represents one of the most consequential hazard categories in hazardous material transportation and transfer operations. The IMDG (International Maritime Dangerous Goods) Code classification classific recognise explosives as Class 1 with distinctive subcategories reflecting decomposition velocities and thermal profiles [19]. Subsequently The recognition that fire incidents involve hazardous materials can lead to secondary explosions, toxic atmosphere generation, and cascading container failures through thermal stress mechanisms creates fire safety assessment risk requirements related to non-hazardous cargo operations The International Maritime Dangerous Goods Code establishes brief regulations addressing separation requirements between incompatible substance classes, accessibility for emergency response vehicles, and proximity for water sources and fire suppression eqquipments in safety assessment [19]. Despite these detailed regulatory frameworks, systematic analysis of intermodal facility incident records reveals that actual operational practices deviate from regulatory specifications frequently. Therefore, Research by the US Coast Guard and industry safety body’s documents incidents that determine that the improper loading of procedures, inadequate container blocking and bracing, and reactive chemical proximity failures precipitated the release of hazardous material, which led to severe consequences [20]. These identified incident patterns surpass the complexity of fire safety assessment frameworks that evaluate both facility infrastructure compliance and operational protocol implementation quality. Liu et al. (2021) introduced a novel fire risk assessment approach for large-scale commercial buildings, which integrates fuzzy hierarchy process with coupling relationship analysis of fire risk factors [21]. The methodology established a suitable hierarchy of fire risk factors across facility management, proper infrastructure maintenance, fire fighting and rescue capability, and potential risk inspection dimensions smoothly. The basic standards of integration of coupling relationships whereby fire risk factors affect overall fire risk profiles represent a substantial methodological refinement for fire safety, which constitutes a system of phenomena rather than an additive accumulation of isolated factors.

Even though the research recognized hazmat emergency response in intermodal contexts that fire incidents involving containerized hazardous materials generate different response challenges, which include identification ambiguity in stacked container arrangements, access restriction for rescue equipment in densely stowed terminal areas, and incomplete shipping documentation in instances where drivers carry accumulated manifests from multiple transfer runs. These operational realities indicate that the fire safety strategy evaluation must ensure the operational protocol addresses documentation completeness, transparent equipment accessibility, and emergency responder pre-incident planning rather than exclusively emphasizing facility design specifications.

2.3. Integration of MCDM Methodologies in Safety Assessment

The literature suggested that the inclining for integration of multiple MCDM methodologies rather than relying upon the single techniques, recognizing that alternative MCDM approaches provide complementary insights reflecting their distinct mathematical properties clearly in an efficient manner. Banu and colleagues (2025) demonstrated that integration of AHP, PROMETHEE, and TOPSIS methodologies substantially emphasized priority-based consistency within HAZOP (Hazard and Operability) study contexts in high-hazard industries [22]. The different nature of these techniques, wherein AHP establishes transparent weighting via hierarchical decomposition, TOPSIS provides a distance-based ranking with computational clarity, and PROMETHEE enables more defensible prioritization outcomes than single-technique approaches continuously. However, the application of MCDM integration to hazardous material transportation has received limited scholarly attention despite the established utility in adjacent domains. Guo and Colleagues (2022) performed a systematic analysis of existing literature that addresses risk assessment models for hazardous materials transportation, identifying that the contemporary frameworks represent uneven sophistication in criterion specification versus weighing methodology development [22]. Practically, the gap between the detailed criterion identification and weighting techniques introduced a principal limitation subsequently in existing hazmat logistics assessment frameworks.

The reviewed literature indicates significant progress in the application of MCDM techniques for safety assessment, hazardous material transportation, and fire risk evaluation. However, most tremendous studies have primarily applied individual decision-making methods or focused on specific aspects of fire safety without giving a chance to a comprehensive comparison of alternative fire safety strategies. Although some recent studies have precisely combined the two MCDM techniques, the integration of AHP, TOPSIS, and PROMETHEE within a unified decision-support framework for hazardous material intermodal transfer operations remains limited. Furthermore, only a limited number of studies have examined the robustness of ranking results through the sensitivity analysis method. These research analysis gaps motivated the development of the proposed integrated framework presented in this study.

Table 2. Research gap analysis Table

S. No	Author year	Research Gap
1	Satty (1980)	The AHP Method Provide a structured way of decision-making, but in real way, expert judgments vary, which is not fully captured in the model.
2	Hwang & Yoon (1981)	TOPSIS works well for ranking alternatives, although it mainly depends on precise data, which is not always available in complex safety problems.
3	Aczél & Saaty (1983	The study improves consistency in comparisons; still, it does not reflect the uncertainty that usually exists in real-world decisions.
4	Brans & Vincke (1985)	PROMETHEE introduces a useful ranking approach, yet defining preference functions can become difficult in practical applications.
5	Buckley (1985)	Fuzzy AHP helps in handling uncertainty, but it does not directly provide a complete solution for ranking final alternatives.
6	Brans et al. (1986)	The method was extended for project evaluation, while its application in hazardous material safety was not considered.
7	Chang (1996)	The extent analysis method improves fuzzy AHP calculations; however, issues may arise when dealing with complex or large hierarchies.
8	Geldermann et al. (2000)	The work focuses on environmental assessment, so areas like fire safety and hazard-based decisions remain unexplored.

9	IMO (2003)	The IMDG Code provides important safety guidelines, but it does not offer a method to compare or select the best safety strategy.
10	Sattayaprasert et al. (2008)	AHP was applied to hazmat routing, though the study remains limited to a single method without combining other techniques.
11	Kilincci & Onal (2011)	Fuzzy AHP has been widely applied in areas such as supplier selection and evaluation; its application in safety-critical systems remains absolutely unexplored and underdeveloped.
12	Behzadian et al. (2012)	The review explains TOPSIS applications in detail, yet the integration with other decision-making methods is not discussed.
13	Noureddine (2019)	The study focuses on transportation risk, but a structured framework for fire safety strategy evaluation is still missing.
14	Wang (2021)	A fire risk model is proposed, although multiple decision-making techniques are not combined for selecting the best strategy.
15	Guo et al. (2022)	The review covers different risk models; however, integrated decision-making approaches are not clearly developed.
16	Guo (2022)	The work emphasizes risk analysis, but practical tools for decision support are not fully provided.
17	US Coast Guard (2024)	The report presents useful incident data, yet it does not lead to a structured decision-making framework.
18	Chanpuypetch (2024)	AHP and TOPSIS are combined in this study, while validation using another method, like PROMETHEE, is not included.
19	Fire Engineering (2024)	Practical challenges are discussed, though no systematic evaluation method is proposed.
20	Abdullah (2024)	Advanced MCDM concepts are discussed, but their application to intermodal fire safety is not explored.
21	Banu et al. (2025)	Integrated MCDM methods are applied in HAZOP studies; however, their use in intermodal fire safety remains limited.

3. Methodology

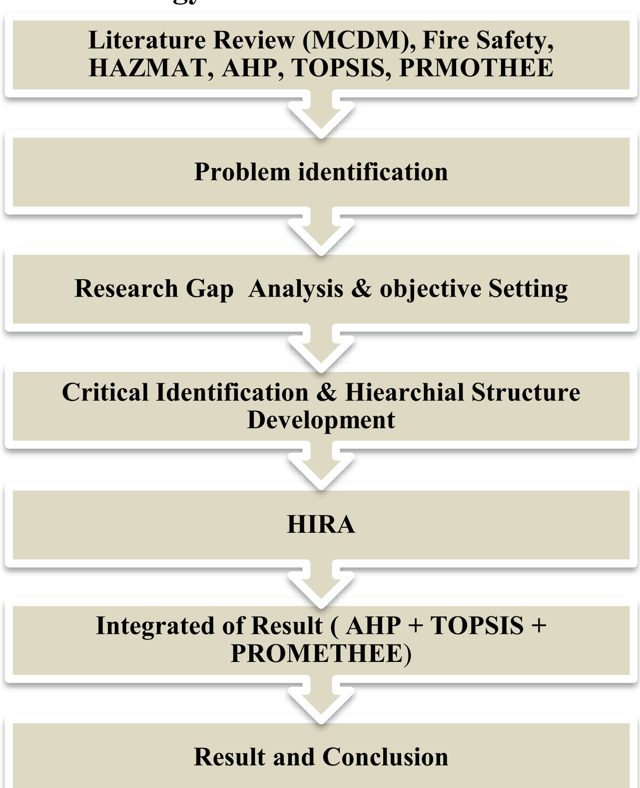

Fig. 1 Methodology Flowchart Diagram

3.1. Hierarchical Structure Development The proposed

The proposed framework follows a four-level hierarchical structure to evaluate fire safety strategies in intermodal hazardous material transfer operations. At the top level of the framework, the primary goal is to identify the

The most suitable and appropriate fire safety strategy. This goal is further divided into four categories: facility infrastructure, operational practices, emergency response capability, and regulatory requirements. The next goal outlines the major key factors within each of these areas, while the final level includes the alternative strategies being assessed subsequently. The infrastructure aspects majorly focus on the physical features of intermodal terminals that influence fire safety management smoothly. This methodology includes the design of safety hazardous material storage areas, where the placement of fire suppression systems, accessibility of emergency exits, and the reliability of detection systems must be considered. In practice, these elements define the environmental studies, preferably within which all operations and response actions take place in a safe manner. The operational side engaged with routine procedures and day-to-day management activities. Some important aspects include the accuracy of the documentation process, inspection of container conditions, proper separation of incompatible substances, and the training level of personnel with awareness and handling hazardous materials. In many cases, the operational gaps are found to be part of incidents even when the physical setup is adequate in some way. Emergency response capability reflects how transparently both the internal teams and external agencies are in handling fire incidents and accidents. This involves pre-incident planning with precautions, availability of emergency equipment near storage zones, coordination with outside response organizations, and the skill level of response personnel management. Even with the preventive systems in place, response reluctance often determines how severe an incident becomes. The final area commits to compliance with relevant standards, measures and legal requirements. This includes adherence to international guidelines such as the IMDG Code, implementation of national transportation rules and regulations, alignment with fire safety codes, and environmental protection measures. Overall, these aspects provide a structural basis for maintaining safety in hazardous material operations.

3.2. Analytic Hierarchy Process Weight Derivation

Unconditionally, the evaluation criteria and pairwise comparison judgments and opinions used in this study were obtained through a transparent, structured questionnaire survey involving domain expertise from hazardous material transportation, fire safety engineering, industrial safety, and academia. Experts were being selected using purposive sampling based on their professional experience and expertise in fire safety management, hazardous material operations, and a multi-criteria decision-making approach. Each expert must have at least five years of relevant industrial or academic experience, ensuring that the collected judgments or opinions are technically reliable and appropriate for the AHP analysis.

Before conducting the final assessment survey, the questionnaire was reviewed to ensure the clarity, transparency, relevance, and completeness of the evaluation criteria and fire safety strategy descriptions in an efficient manner. Few minor revisions were made to improve the wording and overall readability of the questionnaire or their judgements. The proper consistency of the expert judgments was verified using the AHP Consistency Ratio (CR), confirming that the pairwise comparison results were sufficiently reliable and efficient for further analysis. Furthermore, the study involves ten domain experts, which is considered an appropriate sample size for AHP-based decision-making studies. In the AHP methodology, the quality and consistency of the expertise judgments and their opinions are more important than a large number of respondents. The selected expertise possessed relevant industrial and academic experience in hazardous material transportation, fire safety engineering, and industrial safety, ensuring technically reliable evaluations. The acceptable Consistency Ratio (CR) further supports the curriculum reliability of the collected expert judgments or opinions. The proposed framework is divided into four categories to support the evaluation of fire safety strategies in an intermodal hazardous material transfer operations system. At the top level of the framework, the primary aim is to recognise the most appropriate strategy in an efficient manner. This is then divided into four broad areas: infrastructure conditions, operational management practices, response capability and reliability, and compliance requirements. The next level outlines the main factors within each area, while the final level presents the set of alternatives being compared in the framework.

The infrastructure framework focuses on the physical layout and design features that affect the fire safety system. This includes the effective arrangement of hazardous material storage zones, the proper ranking of suppression systems, access to evacuation routes, and the effectiveness of detection systems. These major aspects shape the environment in which both the outline activities and emergency actions take place simultaneously. The operational dimension considers everyday procedures and management practices effectively. It covers the documentation accuracy process, inspection of container condition, control of incompatible substances, and the level of staff training. Experience shows that the gaps in these areas can lead to incidents, even when physical arrangements appear sufficient. Response capability reflects how prepared organizations are to deal with fire-related events efficiently. It involves planning before incidents occur, the availability of equipment near storage areas, coordination with external agencies, and the awareness and knowledge of skills of response teams. Even with preventive measures in place, the outcome of an incident often depends on how effectively it is handled precisely. The final level suggested the alignment with applicable standards and legal obligations. This involves the following international guidelines with measures such as the IMDG Code, applying national transportation rules, meeting and understanding the fire safety requirements, and considering environmental protection measures. Combinely, these elements provide a structured basis for maintaining safety in the hazardous material operations system.

3.3. Topsis Ranking Methodology

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was used to rank different fire safety strategies tremendously based on how close they are to an ideal set of conditions. The options considered include: Strategy A (comprehensive infrastructure upgrade), Strategy B (improved operational practices with enhanced training and awareness), Strategy C (expanded emergency response systems techniques), Strategy D (a combined multidimensional approach), and Strategy E (stronger regulatory compliance monitoring). The performance of each of the options was evaluated using both the numerical data, where available, and expert judgment for qualitative aspects. To ensure comparability, all the values were normalized using vector normalization, where each value was subdivided by the Euclidean norm. These normalized values were then weighted using the priorities obtained from AHP. Thereafter, an ideal case and a worst-case scenario were defined for comparison of each factor. The ideal case represents the best possible value for each factor, while the worst case reflects the least desirable conditions in each factor. The distance of each option from both of these reference points was then calculated precisely. A closeness coefficient was determined in this evaluation way for each option by comparing its distance from the worst case to its total distance from both reference points. Based on these values, the options were ranked harshly, with higher scores indicating better overall performance and closer alignment with the ideal conditions.

3.4. PROMETHEE Ranking Methodology

The Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) was used with TOPSIS to provide an additional ranking perspective and to check the consistency of results. This ranking method is used to compare options directly by using preference functions defined for each evaluation factor. These functions describe how strongly one option is favoured over another based on performance. Among the available types, Gaussian functions were selected for most factors, as they allow preference to increase rather than change abruptly. The required parameters were set through experts consult, based on how much difference in performance is considered meaningful. For each pair of options, a preference value was calculated to show the degree to which one is favoured over the other. These values were then combined using the weights obtained from the AHP process to produce an overall preference measure. Finally, a net flow score was determined for each option by comparing how much it dominates others against how much it is dominated in return. Even though based on these scores, the options were ranked, with higher values indicating better overall.

3.5. Framework Integration and Sensitivity Analysis

The proposed integrated framework combines the results obtained from AHP weighting, TOPSIS, and PROMETHEE by comparing their ranking results and examining total consistency. Results produced by TOPSIS and PROMETHEE were carefully analysed to identify areas where the two methods led to different conclusions. By the way, in such cases, the performance values were revisited carefully, and expert opinions were used to determine whether the variation was due to genuine differences in judgment or possible assessment errors, and to be measured transparently. A transparent analysis was also being carried out by adjusting the weights derived from AHP within reasonable limits and recalculating the rankings under the different scenarios. This helped to recognise whether the results remained stable or changed simultaneously with variations in input values. Finally, the strategies that maintained similar positions across different scenarios were considered more robustness, while those that showed some shifts or changes were identified as sensitive to changes in weighting assumptions. These differences provide additional insight into the reliability of the final rankings.

4. Result and Comparative Analysis

4.1. AHP Weight Derivation Results

Moreover, pairwise comparison results gathered from the expert panel ensure that the acceptable levels of consistency across all hierarchy levels, with consistency ratios ranging from 0.032 to 0.089, remaining with the acceptable limit of 0.1. The transparent use of geometric mean is to combine individual judgments, which produces final weight values that reflect an expert perspective on the relative importance of different factors.

Table. 3 Main Criteria Weight For Fire and Safety Evolution

Parent	Criterion	Weight
FI	Facility infrastructure	0.35
OP	Operational protocols	0.30
ER	Emergency response systems	0.20
RC	Regulatory and standard Compliance	0.15

At the primary level, the assigned weights consist of: facility infrastructure (0.35), operational practices (0.30), response capability (0.20), and regulatory compliance (0.15). These assigned values indicate that experts place the utmost importance on physical design, as it forms the criterian base for overall fire safety performance. Inspite, Operational aspects were considered nearly as an essential part, reflecting their direct influence on day-to-day activities. Response capability also received a significant benefit, highlighting that with preventive measures in place, the outcome of an incident depends largely on how effectively it is managed. Compliance with regulations, apparently necessary, was given the lowest weight, suggesting that meeting formal requirements alone is not enough to ensure comprehensive Safety.

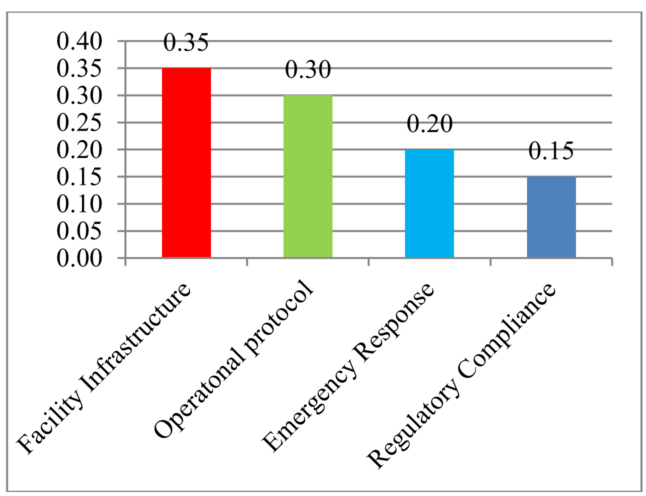

Fig. 2 AHP- Derived Weight Main Criteria for fire safety

Seeing these infrastructure categories, the highest importance was given to storage area design (0.38), followed by fire suppression systems (0.32), granting access to exit routes (0.18), and detection systems (0.12). Further, for operational aspects, container inspection received the greatest emphasis (0.32), followed by substance segregation system (0.28), documentation practices (0.26), and training requirements (0.14). In the case of response capability, pre-incident planning was foremost given the highest value (0.31), with equipment availability (0.28), coordination with external agencies (0.24), and responder training (0.17) following. Under compliance-related factors, adherence to the IMDG Code ranked highest (0.35), followed by national regulations (0.32), fire code alignment (0.22), and environmental considerations (0.11). The fuzzy AHP results, based on triangular fuzzy numbers, showed that the final values remained close to their original estimates, with relatively small variations. This suggests a bias level of agreement among experts. Slightly wider changes were observed within the compliance-related factors, indicating some uncertainty in regulatory elements.

4.2. TOPSIS Ranking Result

The TOPSIS results ranked the five fire safety options as follows: Strategy D (CCI = 0.742), Strategy A (CCI = 0.658), Strategy C (CCI = 0.521), Strategy B (CCI = 0.438), and Strategy E (CCI = 0.312). As a result, the clear gap between Strategy D and the remaining options indicates that a combined approach performs much better than those focusing on a single approach. The top-ranked strategy shows balanced results across all four key factors rather than relying only on one aspect. The second position was received by the infrastructure-focused strategy, which performed well in physical design but remained weaker in operational and response-related aspects. The response-focused strategy was placed in third position, reflecting strong capability in that area but resulting in weaker performance in infrastructure and routine practices. This option centered on operational improvements, which was placed in fourth position, while the compliance-focused option ranked last one, with comparatively lower overall scores. Overall, the results suggest that focusing on only one area leads to limited improvement, whereas a more combined approach delivers better results. Although this observation remains consistent with system safety principles and regulations, it highlights the need to address multiple interconnected elements rather than focusing on a single component.

Table 4. Sub-Criteria Weights with Global Importance

Parent	Code	Sub Criterion	Local Weight	Global Weight
FI	FI 1	Fire detection systems	0.45	0.158
FI	FI 2	Fire suppression systems	0.30	0.105
FI	FI 3	Hazmat segregation	0.25	0.088
OP	OP 1	Handling procedures	0.50	0.150
OP	OP 2	Training and safety culture	0.30	0.090
OP	OP 3	Maintenance and inspection	0.20	0.060
ER	ER 1	On-site firefighting	0.40	0.080
ER	ER 2	Coordination with emergency services	0.35	0.070
ER	ER 3	Emergency planning	0.25	0.050
RC	RC 1	Legal/code compliance	0.50	0.075
RC	RC 2	Audits and reporting	0.30	0.045
RC	RC 3	Performance improvement	0.20	0.030

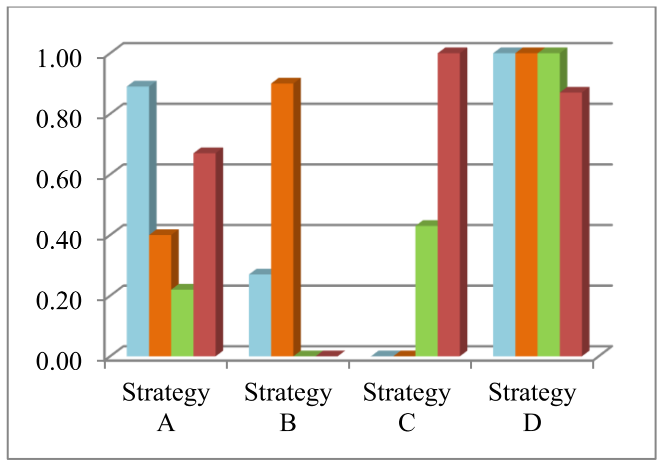

Fig. 3 Performance-based Score on fire Safety

4.3. PROMETHEE Ranking Result

The PROMETHEE II results produced the following order: The PROMETHEE II results produced the following order: Strategy D (+0.384), Strategy A (+0.156), Strategy C (− 0.064), Strategy B (−0.211), and Strategy E (−0.265). This sequence is similar to the TOPSIS results, although the numerical values differ due to the changes in the calculation approach. The final agreement between both methods increases confidence in the final outcome. Accurately, a closer look at pairwise comparisons shows that the top option performs better than all others in most areas. The second option generally performs better than the first one, particularly when compared with the third and fifth options. The third option tends to perform better than the lower-ranked ones, while the fourth shows mixed results depending on the factor being considered, with some strengths balanced by weaker areas.

Table 5. Normalized Performance Scores of Fire Safety Strategies

Strategy	Facility Infrastructure	Operational Protocols	Emergency Response	Regulatory Compliance
Strategy A	0.89	0.40	0.22	0.67
Strategy B	0.27	0.90	0.00	0.00
Strategy C	0.00	0.00	0.43	1.00
Strategy D	1.00	1.00	1.00	0.87

4.4. Sensitivity Analysis Results

A sensitivity analysis was carried out forward by measuring the weights within a ±30% range around the baseline AHP values to examine the stability of results. The integrated approach (Strategy D) examined the top position in 94% of the tested cases, defining strong stability. The infrastructure-focused option (Strategy A) held the second position in 87% of scenarios. The middle-ranked options showed some changes, with Strategies C and B switching places in about 12% of the cases, suggesting moderate changes in input values. The compliance-focused option (Strategy E) consistently remained in the last position across all scenarios. Furthermore, analysis showed that the stability of the top-ranked option majorly depends on maintaining importance for infrastructure and response-related factors. When the weight assigned to infrastructure dropped below 0.24 (from a baseline of 0.32), or response capability fell below 0.18 (from 0.25), its advantage began to be limited. Contrary to this, this suggests that careful attention should be given to these key factors during decision-making action. In particular, where investment in infrastructure is limited, the relative importance assigned to these aspects should be reviewed before selecting a combined approach.

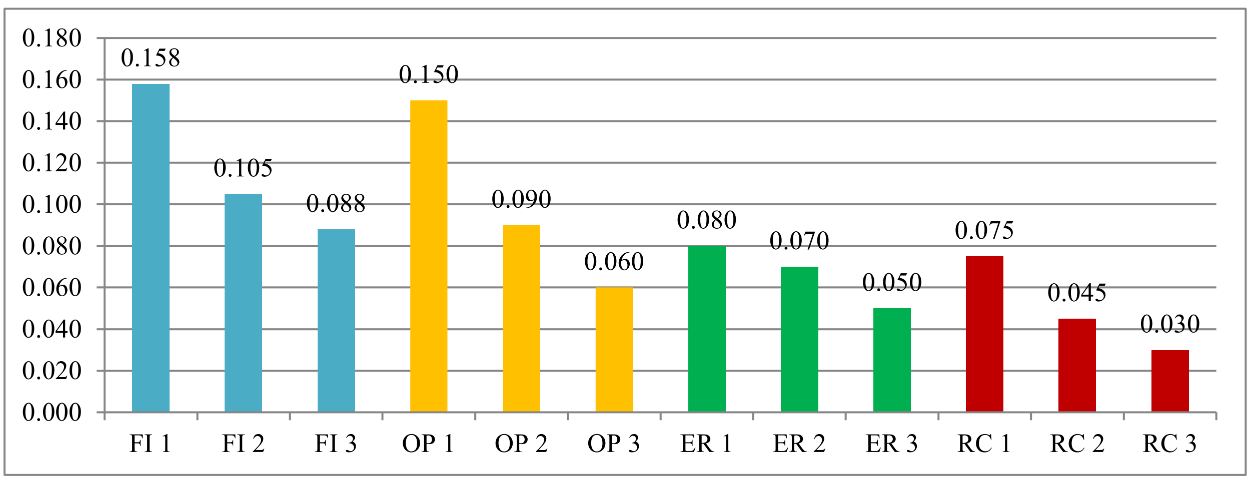

Fig. 4 Global Weight of Sub Criteria for fire Safety

5. Discussion

5.1. Integrated MCDM Framework Advantages

The comparative analysis revealed that integrated MCDM approaches produce superior fire safety strategies relative to single-criterion approaches or ad hoc decision-making processes. Strategy D's consists high ranking across both TOPSIS and PROMETHEE methodologies, combined with its resilience sensitivity analysis variations, providing robust evidence that balanced multi-dimensional fire safety improvement. This analysis reflects fundamental properties of complex operational safety systems wherein fire safety emerges from multiple system components rather than being determined by individual components. The facility given in fire detection and suppression infrastructure operated under deficient operational protocols will experience hazmat handling failures despite technological sophistication. Similarly, outstanding operational protocols implemented within facility designs are leading to a lack of emergency egress capability and cannot fully mitigate consequence severity when fire incidents occur. The MCDM framework's all criterion dimensions encourage decision-makers to recognize and allocate resources accordingly. Subsequently, the integration of AHP extensions to account for expert judgment uncertainty represents a methodological refinement in fire safety assessment. Fuzzy Hazmat operational environments involve genuine uncertainty wherein experts disagree regarding specific criteria weights. Rather than suppressing this uncertainty through a forced decision-making process or averaged judgment, fuzzy set theory enables explicit representation of uncertainty ranges. Decision-makers then examined whether fire safety strategy rankings remain robust across the full range of expert disagreement or whether recommendations prove fragile to reasonable expert judgment opinion. The findings of this study are well established with the previous research, which emphasizes the importance of structured multi-criteria decision-making techniques for safety evaluation. Saaty (1980) introduced the effectiveness of AHP to determine the core importance of evaluation criteria, while Hwang and Yoon (1981) introduced the suitability of TOPSIS for ranking the competing alternatives. Similarly, Brans and Vincke (1985) showed that the PROMETHEE provides a real-time, reliable outranking approach for complex decision problems. However, unlike these studies, the current scenario research incorporates the AHP, TOPSIS, and PROMETHEE within a single decision-support framework for evaluating the fire safety strategies in hazardous material intermodal transfer operations. Furthermore, the inclusion of sensitivity analysis improves the robustness of the obtained rankings, thereby enhancing and encouraging the practical applicability of the proposed framework for an industrial fire safety decision-making approach.

Table 6. Comparison between the existing and present study

Existing Studies	Present Study
Primarily applied a single MCDM technique for decision-making	Integrates AHP, TOPSIS, and PROMETHEE within a unified decision-support framework
Focused on individual fire safety measures or isolated evaluation criteria	Provides a comprehensive evaluation of alternative fire safety strategies using multiple criteria
Limited comparative assessment of alternative fire safety strategies	Systematically prioritizes and ranks fire safety strategies based on multiple decision criteria
Validation of ranking results was rarely addressed	Evaluates the robustness of ranking results through sensitivity analysis
General applications of MCDM in safety management	Specifically developed for hazardous material intermodal transfer operations with practical decision-making support.

5.2. Criterion importance Patterns and Implications

The AHP analysis recommended that the facility infrastructure and operational protocols consists approximately equivalent criterion importance (0.32 and 0.28, respectively), collectively accounting for 60 percent of the overall fire safety strategy evaluation weight.

From experts point of view, distribution reflects that fire safety represents an inherently systems phenomenon where both facility design capacity and operational implementation quality prove to be an essential part. The implication for terminal management ensures the infrastructure investment without concurrent operational protocol development, which produces suboptimal safety outcomes, whereas excellent operational procedures cannot fully compensate for the facility design deficiencies.

The necessary weighting for emergency response systems (0.25) reflects the expert judgement that, inspite of rigorous prevention efforts, residual fire risk persists in hazmat operations. This weighting validates in pre-incident planning for safety, safety equipment accessibility, mutual aid coordination, and competency as a direct fire safety strategy rather than peripheral support functions.

The actual lower regulatory compliance weighting (0.15) does not suggest conformity, which represents an unimportant consideration, but rather it reflects expert judgement that the regulated necessary baseline standards that will be responsible operators should exceed. Although it exclusively emphasising regulatory compliance without addressing prevention and response dimensions, it represents insufficient fire safety management.

5.3. Implementation Pathway and organizational Change

These introduced frameworks suggest an implementation pathway where integrated multi-dimensional fire safety strategy development should proceed through strategic planning, based on criteria-specific performance assessment, and phased improvement prioritization. Initially strategic planning phase should accommodate safety engineers, terminal operations personnel, and emergency response representatives with alternatives to validate the hierarchical criterion structure and confirm appropriateness for specific terminal contexts, even though modifications to primary criteria or sub-criteria may prove essential in facilities with unusual configurations or specialized hazmat transfer functions. Criterion-specific based performance should analyse existing facility and operational performance against each sub-criterion through facility audits, operational procedure documentation review, and emergency response capability evaluation. This assessment phase generates the quantitative and qualitative data inputs required for TOPSIS and PROMETHEE evaluation. Differences between regulatory compliance and optimal performance often emerge during this assessment phase, revealing gaps between minimum regulatory requirements and best-practice fire safety standards. Phased improvement priortizaly should allocate financial and organizational resources toward fire safety improvements that address criterion dimensions to achieve the lowest current performance scores, subject to practical constraints regarding implementation feasibility and investment capacity. The framework's capacity for these analyses enables to explore alternative investment scenarios, allowing terminal management to understand trade-offs between different improvement pathway sequences.

5.4. Research Limitations and Future Directions

The recognised framework necessarily incorporates several limitations warranting acknowledgment and discussion. The research organised an expert panel from a geographic region to handle potentially regional regulatory environments and operational practices without universal applicability across diverse international jurisdictions. Further, Fire safety requirements and operational practices vary continuously between maritime terminals, road transfer facilities, and rail intermodal yards, but the framework was developed primarily with maritime and port terminal contexts in mind. Adaptation of criterion specifications and weighting distributions for non-maritime intermodal Longitudinal research tracking fire safety ensures the outcomes in terminals implementing alternative strategic approaches identified through the MCDM framework would enhance understanding, predicted performance differences translate into measurable safety outcome improvements. As a result, Incident rate comparison, near-miss frequency analysis, and emergency response time documentation would provide empirical validation of the framework's predictive capacity. The research assumed that the five fire safety strategy alternatives represent separate, mutually exclusive options requiring the selection of one optimal approach. In these real world terminal management, it may optimally implement combinations or sequences of multiple strategies simultaneously. Subsequently, extension of the MCDM framework to address portfolio decision problems where multiple non- mutually-exclusive strategies are simultaneously implemented represents a valuable future development.

6. Implication of Research

This aspect of research provides important practical and theoretical insights for improving fire safety management in hazardous material intermodal transfer operations. One of the key implications is that decision-makers should avoid focusing on a single aspect of safety approach, such as only infrastructure or regulatory compliance. Instead, the earlier analysis clearly suggests that a balanced and integrated approach gives better results in reducing overall risk. The strong performance of the integrated strategy (Strategy D) suggested that combining the infrastructure improvements, operational and functional protocols, and emergency response systems leads to convenient, effective safety outcomes and measures.

Although from a practical point of view, terminal managers and safety engineers can make use of this framework as a decision-maker tool to prioritize investments. Rather than relying on traditional methods, they can introduce different safety strategies based on multiple criteria. This helps in making more transparent, logical, and justifiable decisions, especially in high-risk environments where safety failures can cause serious consequences.

Another necessary implication is related to resource allocation. The study highlights that facility infrastructure and operational protocols carry forward the highest importance weights, which means that first of all, organizations should prioritize funding, improvements and developments in these areas. However, the role of emergency response systems is also mandatory, indicating that preparing before accidents is just as important as preventing them.

The research also emphasized academic knowledge by demonstrating how integrating multiple decision-making techniques (AHP, TOPSIS, and PROMETHEE) can improve consistency and reliability in results. These suggest that future studies in safety engineering and risk management should consider combined approaches rather than relying on a single method approach.

Additionally, the inclusion of fuzzy logic in the model reflects real-world uncertainty over expert judgment. This makes the framework a more realistic and adaptable approach to overcome the different operational conditions. It implies that decision-making in safety-critical environments should acknowledge uncertainty instead of ignoring it.

7. Conclusion

Furthermore, the systematic evaluation of fire safety strategies in hazardous material intermodal transfer operations requires decision support frameworks that are capable of addressing different types of criterion dimensions, while accommodating inherent uncertainty in expert judgment. The integrated MCDM approach combining AHP weight derivation, TOPSIS ranking, and PROMETHEE analysis provides a crucial platform for fire safety strategy prioritizing in the safety of complex operational environments. This framework's analysis of five alternative fire safety strategies focuses on multidimensional approaches that outperform single-dimension strategies, with ranking robustness validated through methodological triangulation and sensitivity analysis.

The interconnected empirical finding suggests that facility infrastructure, operational protocols, and emergency response systems represent similarly important criterion categories, which suggests the terminal fire safety management and requires balanced investment across multiple domains rather than concentrated emphasis on isolated dimensions. For terminal management, the framework emphasizes best practices guidelines from international standards, including the IMDG Code and national hazmat regulations, through structured, systematic evaluation accommodating facility-specific constraints and risk profiles. The integration of fuzzy logic extensions and sensitivity analysis to enable decision-makers to evaluate strategy' robustness across reasonable expert judgment variations, supporting defensible capital allocation with financial and safety implications For ensuring safety research, the framework demonstrates practical application of MCDM methodologies to real-world operational decision and identifies opportunities for refinement through incorporation of coupling relationships among fire safety factors, integration of historical incident data weighting, and extension to portfolio decision problems addressing simultaneous multi-strategy implementation. The fire safety strategy evaluation context provides a advance way in MCDM methodology development and validation in complex socio-technical systems characterising both quantifiable performance dimensions and irreducibly qualitative factors where expert judgment remains mandatory.

Future research should prioritize the collection of incident data correlating between fire safety strategy implementation and actual safety outcome improvements, thereby providing empirical validation of the framework's predictive capacity. Additionally, comparative analysis of framework systems across different intermodal facility types would clarify whether criterion importance weightings generalize across maritime, rail, and road transfer contexts or require domain-specific calibration. In context, Longitudinal tracking of operational implementation experiences with strategies that will reduce practical barriers to strategy adoption and identify necessary institutional or technological adaptations to realize theoretical safety improvements in the actual operational environment.

Conflicts of Interest

In this context, the author declares that there are no conflicts of interest related to the publication of this paper. The research was conducted independently, without any commercial or financial relationships that could be viewed as potential conflicts of interest.

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