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Development of a Fire Safety Assessment Model for Buildings in Poland Using the Analytic Hierarchy Process: Validation Through Pilot Study

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Abstract

Despite advances in engineering, fire safety improvements have plateaued in developed nations, necessitating a reassessment of resource allocation. This study develops a comprehensive fire safety assessment model for the Polish context using the Analytic Hierarchy Process (AHP). A panel of ten experts—comprising fire safety inspectors, State Fire Service officers, and architects—evaluated safety through a two-dimensional framework: the Fire Hazard Index (FHI) and Fire Safety Index (FSI). The results reveal a critical asymmetry: human factors (0.228) and combustible materials dominate the hazard landscape, whereas intelligent AI/IoT systems (0.4133) and passive protection (0.2113) offer the highest potential for safety enhancement. A novel "convergence–divergence" phenomenon was identified: hazard-focused assessments produce convergent priorities across building types (span 0.116), implying universal mitigation needs (e.g., education), while protection-focused assessments yield divergent priorities (span 0.250), justifying targeted investment. Specifically, healthcare facilities (ZL II) require disproportionate protection investment (priority 0.310). The study concludes that sustainable fire safety strategies must combine universal hazard mitigation with targeted technological interventions, offering a data-driven framework for policy optimization in Poland.

Keywords: fire safety assessment; Analytic Hierarchy Process; AHP; Fire Hazard Index; Fire Safety Index; intelligent systems; AI/IoT; building fire protection; multi-criteria decision analysis; performance-based design

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1. Introduction

Building fires represent persistent threats to life safety, property protection, and urban sustainability despite substantial advances in fire protection engineering and regulatory frameworks over recent decades [1–4]. Annual global fire losses exceed $300 billion USD, with developed nations experiencing 1–2 fire deaths per 100,000 population—rates that have plateaued despite technological improvements [5]. This stagnation suggests that the incremental refinement of conventional fire safety approaches may yield diminishing returns, necessitating a systematic reassessment of which factors most critically influence fire outcomes and how resources should be allocated to maximize safety improvement.

Contemporary buildings present increasingly complex fire safety challenges. Modern construction employs novel materials—particularly composite facade systems and

advanced interior finishes—whose combustibility characteristics differ substantially from traditional materials, sometimes with catastrophic consequences, as demonstrated by recent high-profile incidents [6,7]. Building functions have diversified beyond traditional residential, commercial, and industrial categories to include mixed-use developments, healthcare complexes serving aging populations with mobility impairments, and entertainment venues accommodating thousands of occupants in architecturally intricate environments. Occupancy patterns have intensified through urbanization and land-use densification, increasing both potential casualty numbers and evacuation complexity. These trends collectively demand fire safety assessment methodologies capable of systematically evaluating multiple interacting factors while accommodating stakeholder disagreement regarding priorities.

The Analytic Hierarchy Process (AHP), developed by Saaty [8] as a multi-criteria decision analysis methodology, has emerged as powerful tool for fire safety assessment where numerous factors interact, quantitative data remain sparse, and expert judgment provides the primary knowledge source. AHP decomposes complex decision problems into hierarchical structures, enables systematic evaluation through pairwise comparisons, and synthesizes individual judgments into quantitative priority weights while maintaining consistency validation [8–10]. Fire safety applications have successfully employed AHP for high-rise building risk assessment [11,12], shopping mall evacuation planning [13,14], heritage structure protection [15,16], and industrial facility hazard analysis [17]. More recent applications have extended this methodology to schools for vulnerable populations, large commercial buildings [18], and BIM-integrated multi-stakeholder models [19], confirming AHP's continued relevance in contemporary fire safety research. These studies demonstrate AHP's effectiveness in structuring fire safety complexity, though they typically focus on establishing priority rankings within single dimensions rather than examining relationships between hazard sources and protective capabilities.

Recent technological developments introduce new dimensions to fire safety assessment. Intelligent systems incorporating artificial intelligence and Internet of Things technologies offer capabilities fundamentally unavailable through conventional protection: real-time occupancy tracking informing dynamic evacuation routing, predictive analytics identifying emerging risks before ignition, environmental monitoring networks detecting threats with greater sensitivity than traditional point sensors, and Building Information Modeling integration enabling coordinated emergency response [20–24]. However, these technologies remain relatively novel, with limited deployment data validating anticipated benefits and substantial implementation barriers (high costs, integration complexity, regulatory uncertainty, limited professional expertise) inhibiting adoption. Expert assessment of intelligent systems' potential relative to established protection approaches therefore becomes critical for guiding investment strategies and regulatory development.

Simultaneously, the growing recognition of human factors' role in fire causation challenges engineering-centric approaches dominating fire safety practice. International incident statistics consistently demonstrate that human error—including improper equipment operation, procedural non-compliance, delayed response to alarms, and risky behaviors—accounts for the majority of fire initiations and casualty outcomes [25,26]. Yet fire safety interventions historically emphasized technical systems (detection, suppression, compartmentation) over behavioral interventions (education, training, procedural enforcement), partly because engineering solutions appear more controllable and measurable. Systematically quantifying human factors' relative importance compared to technical hazards would inform whether substantial resources should be redirected from incremental technical improvements toward behavioral and organizational interventions.

The Polish context presents distinctive characteristics meriting dedicated assessment. Poland's building stock combines historical structures predating modern fire codes with

contemporary construction employing advanced materials and systems. The regulatory framework—grounded in technical requirements (Warunki Techniczne) and ministerial regulations—establishes comprehensive prescriptive standards for technical systems while providing less detailed guidance for emerging technologies and behavioral management. Building classification according to funkcja użytkowa (functional use) employs categories (ZL I–V for various occupancy types, PM for production/warehousing) that do not map directly to international taxonomies, limiting the direct application of foreign research findings. Fire service organization through Państwowa Straż Pożarna (State Fire Service) with specific operational protocols and training standards influences protective strategy effectiveness. These Poland-specific conditions suggest that fire safety priorities established through international research may not accurately reflect Polish circumstances, necessitating dedicated assessment grounded in local expertise and the regulatory context.

This study addresses three research objectives: (1) develop a comprehensive AHP-based fire safety assessment framework applicable to Polish building categories, decomposing overall safety into the Fire Hazard Index (FHI), quantifying risk sources, and Fire Safety Index (FSI), evaluating protective capabilities; (2) quantify the relative priorities of specific hazard factors and protection measures through structured expert consultation with professionals spanning fire safety inspection, emergency response, and architectural design; and (3) demonstrate framework application through a comparative analysis of building categories and sensitivity testing, revealing how strategic orientation—emphasizing hazard reduction versus protection investment—alters resource allocation implications.

The framework advances fire safety assessment methodology in three ways. First, it maintains an analytical separation between hazard sources and protective capabilities rather than aggregating them into unidimensional risk scores, enabling an examination of whether buildings face similar hazards but differ in protection needs—a distinction with direct policy relevance for universal versus targeted interventions. Second, it systematically varies relative weighting between hazards and protections, revealing convergence–divergence patterns invisible in single-weighting analyses: hazard-focused assessment produces convergent priorities suggesting universal mitigation needs, while protection-focused assessment yields divergent priorities indicating targeted investment opportunities. Third, it establishes a transparent methodology for exploring how different strategic orientations alter building category priorities, enabling evidence-based policy deliberation regarding values-dependent trade-offs rather than presuming a single "correct" weighting.

The study contributes to sustainable fire safety—an emerging research domain recognizing that effective protection must balance life safety, property preservation, business continuity, environmental impact, and community resilience rather than narrowly optimizing single objectives [27]. By identifying which interventions offer the greatest safety improvement potential (intelligent systems, passive protection) versus which present the greatest implementation challenges (human factors, combustible materials), the framework informs resource allocation strategies maximizing safety gains within realistic constraints. The convergence–divergence finding particularly supports sustainability principles: universal hazard mitigation (education, material restrictions) distributes benefits broadly across building stock and occupant populations, while targeted protection enhancement (intelligent systems in healthcare facilities) concentrates resources where vulnerability and benefit potential align.

The remainder of this article proceeds as follows. Section 2 describes the AHP methodology, expert panel composition, hierarchical model structure spanning FHI and FSI subcriteria, data collection procedures, and analysis approaches including consistency validation and sensitivity testing. Section 3 presents results examining FHI priorities, FSI priorities, comparative FHI-FSI assessment under equal weighting, hierarchical weighting impacts

revealing convergence–divergence patterns, and sensitivity analysis across the full weighting spectrum. Section 4 discusses the principal findings in the context of the existing literature, the theoretical implications of convergence–divergence phenomenon, policy and practice recommendations for diverse stakeholder groups, methodological contributions and limitations, and future research directions. Section 5 concludes with a synthesis of key findings and implications for advancing fire safety science and practice in Poland and internationally.

2. Materials and Methods

2.1. Research Design and Methodological Framework

This pilot study employed the Analytic Hierarchy Process (AHP) to construct a comprehensive fire safety assessment model for Polish buildings. The research design integrated three methodological components: (1) hierarchical model development grounded in Polish technical regulations (Warunki Techniczne, WT) and ministerial fire protection ordinances, supplemented by international fire safety frameworks; (2) expert judgment elicitation through structured pairwise comparison questionnaires employing Saaty's fundamental scale [8]; and (3) weight synthesis using the Aggregation of Individual Judgments (AIJ) approach with geometric mean aggregation, selected over Aggregation of Individual Priorities (AIP) to preserve decision-making independence and avoid premature consensus [28,29].

The study design followed established AHP protocols while incorporating fire safety-specific adaptations. First, the hierarchical structure was developed through iterative consultation with domain experts and regulatory analysis, ensuring a comprehensive coverage of hazard sources and protective capabilities relevant to the Polish context. Second, pairwise comparison matrices were constructed systematically, with each expert independently evaluating the relative importance of elements at each hierarchical level. Third, consistency validation was performed for all matrices using consistency ratio (CR) calculations, with a $CR < 0.10$ threshold applied as per Saaty's recommendations [8]. Fourth, sensitivity analysis systematically varied FHI/FSI weighting ratios to examine robustness and reveal strategic orientation impacts on building category priorities.

A key methodological assumption of the AHP framework is the independence of subcriteria within each hierarchical level. In practice, interactions may exist between certain elements—for example, the effectiveness of intelligent evacuation systems (FSI) depends partly on the integrity of passive compartmentation (FSI), and the severity of human factor hazards (FHI) may be moderated by safety management systems (FSI). The independence assumption simplifies the analysis and is standard AHP practice [8], but may not fully capture synergistic or antagonistic interactions between subcriteria. Where such interdependencies are suspected, the Analytic Network Process (ANP) offers a methodological extension that explicitly models feedback relationships, albeit at substantially greater complexity. The present study acknowledges this assumption; practitioners using the framework for detailed investment planning are advised to complement AHP-derived priorities with domain-specific interaction analysis.

Ethical considerations were addressed through informed consent procedures, professional anonymity protection, and voluntary participation protocols. While formal ethical approval was not required for expert consultation research under Polish regulations governing research conduct, the study adhered to established professional ethics standards and data protection requirements (GDPR compliance). Participants received written information describing study objectives, time requirements, data usage, and confidentiality safeguards prior to providing consent.

2.2. Expert Panel Selection and Composition

The expert panel comprised 10 professionals selected through purposive sampling to ensure complementary expertise across fire safety domains essential for comprehensive assessment. Selection criteria required: (1) a minimum of 10 years professional experience in the fire safety field; (2) current professional certification or licensing for their respective role; (3) direct involvement in Polish building fire safety through inspection, response, or design activities; and (4) demonstrated expertise through publications, training delivery, or recognized professional contributions.

Panel composition balanced three professional categories representing distinct perspectives on fire safety priorities. Three certified fire safety inspectors (rzeczoznawcy ds. zabezpieczeń przeciwpożarowych) contributed expertise in regulatory compliance assessment, building evaluation procedures, and code interpretation. These participants averaged 16.3 years of experience (SD = 3.8) and held certifications issued by the Ministry of Interior and Administration following comprehensive examination processes. Three Państwowa Straż Pożarna (State Fire Service) officers contributed operational and tactical knowledge regarding emergency response, building access requirements, firefighting effectiveness, and system reliability under incident conditions. These participants averaged 18.7 years of service (SD = 5.2) and held ranks of captain or above, indicating substantial command experience. Four licensed architects specializing in fire safety design contributed knowledge of architectural integration challenges, material selection implications, egress design optimization, and building system coordination. These participants averaged 12.5 years of experience (SD = 4.1) and maintained active architectural licenses with demonstrated fire safety specialization through project portfolios.

This multi-perspective composition ensured that priority assessments reflected comprehensive understanding spanning regulatory requirements (inspectors), operational feasibility (fire service), and design implementation (architects). Diversity across professional roles mitigates single-perspective biases that can occur when expert panels derive from homogeneous backgrounds [28]. The panel size (n = 10) exceeds the minimum requirements for AHP expert consultation (typically 5–7 participants) while remaining manageable for consistency analysis and coordination [29].

Geographic distribution spanned three voivodeships (Greater Poland, Masovian, Lower Silesian) encompassing urban, suburban, and mixed development contexts. This distribution ensures that priorities reflect diverse building stocks and operational environments rather than location-specific conditions. However, all participants worked primarily in urban or suburban contexts; rural fire safety perspectives remain underrepresented, representing a potential limitation for generalization to low-density areas. Consequently, the findings and derived priority weights should be interpreted as primarily applicable to urban and suburban building stock. Future studies should explicitly recruit experts from rural voivodeships and smaller municipalities to assess whether convergence–divergence patterns and subcriteria weights hold across settlement types.

2.3. Hierarchical Model Structure and Element Definition

The AHP hierarchy comprised four levels: (1) overall goal; (2) main criteria (FHI and FSI); (3) subcriteria decomposing hazards and protections; and (4) alternatives representing Polish building categories. The specific subcriteria were selected through a two-stage process: first, a systematic review of Polish technical regulations (Warunki Techniczne) and fire protection ordinances identified all factors explicitly addressed in the regulatory framework; second, three preliminary consultations with domain experts refined this list by adding factors considered practically significant but not yet codified (notably, intelligent AI/IoT systems) and removing factors with negligible discriminatory value across building

categories. This iterative approach ensured that the hierarchy reflects both regulatory reality and professional practice in Poland. To ensure clarity and conciseness, the definitions of the FHI/FSI subcriteria and building categories are summarized in Tables 1 and 2, respectively.

Table 1. Definitions of Fire Hazard Index (FHI) and Fire Safety Index (FSI) subcriteria.

Index	Subcriterion	Description and Scope
FHI	Human factors	Occupant behaviors, safety awareness, procedural non-compliance, staff training levels, and organizational safety culture.
	Modern composite facades	External wall systems (e.g., ACP), core combustibility, cavity configurations, and joint detailing enabling vertical fire spread.
	Interior finishing materials	Wall/ceiling coverings, furnishings, fuel load, and toxic emission characteristics.
	Occupancy density	Occupants per unit area, mobility limitations, demographic characteristics, and evacuation complexity.
	Gas installations	Natural gas/LPG systems, piping integrity, leak detection, and automatic shutoff mechanisms.
	Building surroundings	External exposure (adjacent structures, vegetation), fire service access roads, and wildland–urban interface.
	Electrical installations	Distribution systems, wiring condition, maintenance protocols, and compliance with PN-EN standards.
FSI	Intelligent systems (AI/IoT)	AI-driven evacuation guidance, real-time IoT environmental monitoring, BIM/digital twin integration, and predictive analytics.
	Passive protection measures	Fire-rated structural assemblies, compartmentation, protected egress routes, and non-combustible material specifications.
	Fire service capabilities	External intervention effectiveness, access infrastructure, water supply reliability, and pre-incident planning.
	Active protection systems	Automatic detection/suppression (sprinklers, mist), alarm communication, and manual firefighting equipment.
	Emergency power/comms	Backup generators, battery systems for critical loads, and redundant communication pathways.
	Safety management systems	Procedural capabilities, documented plans, regular testing protocols, and evacuation drills.

Table 2. Polish building category classifications (Alternatives) defined by functional use.

Category	Functional Description	Key Characteristics
ZL I	Public Assembly	Theaters, cinemas, shopping centers, sports arenas. Large occupant loads, complex circulation, users unfamiliar with layout.
ZL II	Healthcare/Childcare	Hospitals, nurseries, nursing homes. Vulnerable populations (elderly, mobility-impaired) requiring assisted evacuation; 24 h occupancy.
ZL III	Office/Admin	Offices, schools, banks. Moderate density, able-bodied populations, defined operating hours, users familiar with layout.
ZL IV	Multi-family Residential	Apartments, condominiums. Sleeping occupants (delayed detection), private spaces limiting access.
ZL V	Collective Residential	Hotels, dormitories, barracks. Transient populations unfamiliar with layout, 24 h occupancy, hospitality service staff.
PM	Production/Warehouse	Factories, logistics centers. Lower occupancy density, high fuel loads, specific industrial hazards.

2.4. Data Collection Procedures

Expert assessments were elicited through structured questionnaires implementing pairwise comparison matrices at each hierarchical level. Data collection occurred during individual consultation sessions (90–120 min per participant) conducted between October 2024 and January 2025. Individual sessions were employed rather than group workshops to prevent groupthink phenomena, social pressure toward consensus, or dominance by vocal participants [28].

Each questionnaire employed Saaty's fundamental scale for pairwise comparisons [8]: 1: Equal importance—3: Moderate importance of one over another—5: Strong importance—7: Very strong importance—9: Extreme importance—2, 4, 6, 8: Intermediate values—Reciprocals (1/2, 1/3, . . ., 1/9): Inverse comparisons.

The questionnaire structure encompassed multiple comparison matrices: FHI subcriteria pairwise comparisons (7 × 7 matrix, 21 judgments)—FSI subcriteria pairwise comparisons (6 × 6 matrix, 15 judgments)—building category comparisons relative to each FHI subcriterion (7 matrices of 6 × 6, 105 judgments)—building category comparisons relative to each FSI subcriterion (6 matrices of 6 × 6, 90 judgments)—FHI versus FSI relative importance at criteria level (1 × 1, 1 judgment).

Total comparison requirements per expert: 232 individual judgments. This substantial cognitive demand represents a notable methodological limitation. Although questionnaires were divided into three sections administered across multiple sessions where needed and matrix presentation order was randomized to distribute potential fatigue effects, cumulative cognitive fatigue across 232 judgments cannot be fully excluded. Fatigue-induced inconsistency in later matrices is a recognized risk in comprehensive AHP applications [29]. Future studies should consider abbreviated hierarchies or adaptive questioning strategies that reduce comparison burden without sacrificing hierarchical coverage and should systematically monitor response times as a proxy indicator of participant engagement across the questionnaire sequence.

Prior to data collection, orientation sessions familiarized participants with AHP methodology, interpretation of comparison scales, and specific definitions of subcriteria. Written materials provided standardized element descriptions ensuring consistent interpretation across participants. Experts were instructed to base assessments on professional experience rather than attempting formal code compliance analysis, focusing on the relative contribution of factors to fire safety outcomes under typical Polish building conditions. Several measures were taken to control potential expert bias. First, individual sessions (rather than group workshops) prevented social conformity pressure and dominance by vocal participants [28]. Second, the AIJ aggregation method using geometric mean synthesis reduces the influence of outlier judgments while preserving the reciprocal property of pairwise comparisons [29]. Third, standardized written definitions of all subcriteria were provided to minimize idiosyncratic interpretation differences across the three professional groups. Fourth, consistency ratio monitoring (CR < 0.08 threshold) identified any participant whose judgments showed internal incoherence. No matrices required revision, indicating that experts engaged consistently throughout the elicitation process.

2.5. Data Analysis and Weight Derivation

Individual expert comparison matrices were aggregated using the Aggregation of Individual Judgments (AIJ) approach with geometric mean synthesis [28]. For each pairwise comparison position in the matrix, the geometric mean of individual expert assessments was calculated:

$$\mathbf{a_ij(group)=(\prod[k=1\ to\ n]\ a_{ij(k)})^{\frac{1}{n}}}$$

where **a_ij(group)** represents the aggregated comparison value, **a_ij(k)** denotes the **k**-th expert's assessment, and n indicates the number of experts. The geometric mean was selected over the arithmetic mean because it preserves the reciprocal property essential for AHP (if element A is 3 times more important than element B, then B is 1/3 times as important as A) and reduces the influence of extreme outlier judgments [29].

Aggregated comparison matrices were processed using SpiceLogic AHP ver. 4.2.7 software to derive priority weights through eigenvalue calculation. For each comparison matrix, the principal eigenvector was extracted and normalized to sum to unity, yielding local priority weights for elements at each hierarchical level. Global priorities for building categories were calculated through a multiplicative synthesis of local weights along hierarchical paths from alternatives through subcriteria and criteria to overall goal:

Global Priority = (FHI Weight) × (FHI Subcriterion Weight) × (Building Priority on FHI Subcriterion) + (FSI Weight) × (FSI Subcriterion Weight) × (Building Priority on FSI Subcriterion)

Consistency analysis employed the consistency ratio (CR), calculated as the ratio of the Consistency Index (CI) to the Random Index (RI). CI was derived from the maximum eigenvalue (λ_max) using the formula

$$\mathbf{CI = (\lambda_max - n)/(n - 1)}$$

where n represents the matrix dimension. Following Saaty's guidelines [8], matrices with CR < 0.10 were deemed acceptably consistent, while those exceeding this threshold were reviewed with participants for potential revision. All comparison matrices in this study achieved CR values below 0.08, indicating satisfactory judgment consistency across all expert assessments.

Sensitivity analysis examined the impact of varying FHI/FSI relative weights on building category priorities. Three scenarios were evaluated: Equal weighting: FHI = FSI = 0.50 (baseline scenario)—Extreme FHI emphasis: FHI = 0.90, FSI = 0.10 (importance ratio 9:1)—Extreme FSI emphasis: FHI = 0.10, FSI = 0.90 (importance ratio 1:9).

Extreme weighting employed a Saaty scale value of 9 (extreme importance) to generate the maximum differentiation between scenarios, enabling an examination of how strategic orientation fundamentally alters priorities rather than producing marginal adjustments. Additional intermediate scenarios (70/30, 30/70) were calculated to examine transition dynamics but are presented selectively to maintain clarity.

2.6. Validation and Quality Assurance

Multiple validation approaches ensured result reliability:

(1) Consistency validation: All matrices achieved CR < 0.08, substantially exceeding the acceptance threshold (0.10), confirming coherent expert judgments.
(2) Completeness verification: All 232 required judgments were obtained from all 10 participants with no missing data, ensuring comprehensive coverage.
(3) Outlier analysis: Individual expert weights were examined for extreme deviations from group consensus. No participants showed systematic divergence suggesting misunderstanding or disengagement.
(4) Face validity assessment: Derived priorities were reviewed with a subset of the expert panel (n = 4) for reasonableness verification. Participants confirmed that weight patterns aligned with professional intuition while noting some surprising magnitudes (particularly intelligent systems' dominance), stimulating reflection on technology potential.

(5) Literature triangulation: Major findings (human factors dominance, passive protection importance) were compared against international fire safety research, confirming an alignment with established patterns while identifying novel elements (convergence–divergence phenomenon) advancing beyond the existing literature.

These validation procedures establish confidence that results reflect robust expert consensus grounded in professional knowledge and experience rather than methodological artifacts or data quality issues.

3. Results

3.1. Overview of AHP Analysis Framework

The analysis yielded priority weights across four hierarchical levels. All comparison matrices achieved consistency ratios (CRs) below 0.08, confirming judgment reliability.

3.2. Fire Hazard Index (FHI): Identifying Critical Risk Sources

Fire Hazard Index analysis quantified the relative importance of seven factors. As shown in Table 3, human factors emerged as the single most critical hazard source.

Table 3. Fire Hazard Index (FHI) subcriteria priority weights and rankings.

Rank	FHI Subcriterion	Local Weight
1	Human factors	0.228
2	Modern composite facades	0.210
3	Interior finishing materials	0.207
4	Occupancy density	0.143
5	Gas installations	0.095
6	Building surroundings	0.079
7	Electrical installations	0.039

The dominance of human factors **(0.228)** indicates that the weakest link is human performance rather than hardware. Material properties (facades and finishes) collectively account for **41.7%** of the hazard weight. Conversely, electrical installations received the lowest weight **(0.039)**, reflecting effective mitigation through existing rigorous Polish regulations Figure 1.

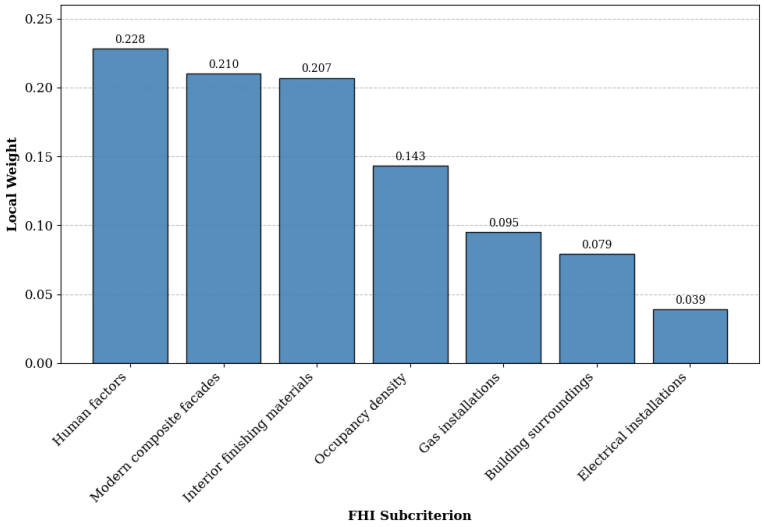


Figure 1. Fire Hazard Index (FHI) priority weights visualization showing dominance of human factors, composite facades, and finishing materials.

3.3. Fire Safety Index (FSI): Evaluating Protective Capabilities

The analysis of protective categories reveals a paradigm shift. As detailed in Table 4, intelligent systems achieved the dominant priority.

Table 4. Fire Safety Index (FSI) subcriteria priority weights and rankings.

Rank	FSI Subcriterion	Local Weight
1	Intelligent systems (AI/IoT)	0.4133
2	Passive protection measures	0.2113
3	Fire service operational capabilities	0.1740
4	Active protection systems	0.0913
5	Emergency power and communication	0.0683
6	Safety management systems	0.0418

The magnitude of intelligent systems' priority **(41.33%)** reflects expert consensus that AI/IoT offers capabilities unavailable through conventional protection, such as dynamic evacuation guidance. Passive protection remains critical **(21.13%)** as a foundational defense Figure 2.

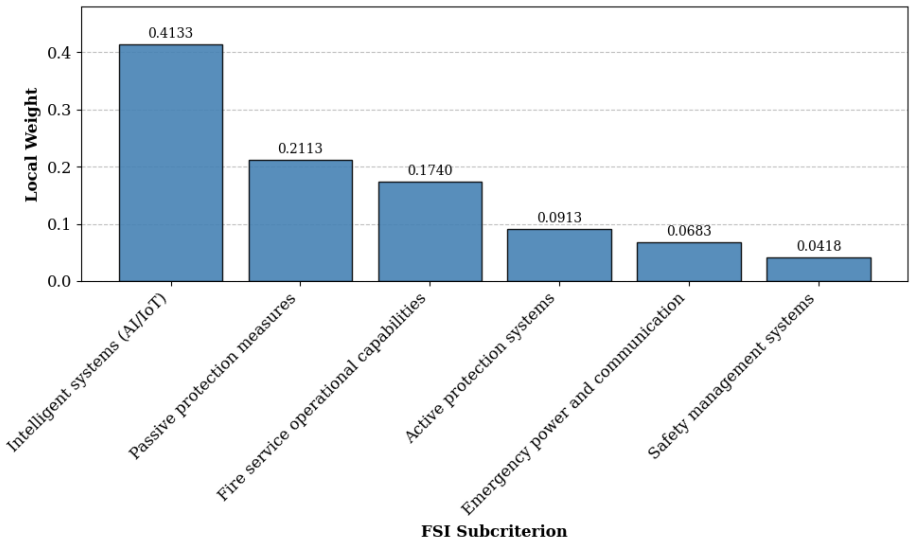


Figure 2. Fire Safety Index (FSI) priority weight visualization demonstrating the dominant importance of intelligent AI/IoT systems.

These results underscore a key advantage of the proposed two-dimensional FHI/FSI framework over traditional single-dimension risk scoring approaches [12,13]: by analytically separating hazard sources from protective capabilities, the model reveals that the factors presenting the greatest hazard (human factors, combustible materials) are distinct from those offering the greatest protective leverage (AI/IoT, passive protection). A conventional aggregated risk index would obscure this asymmetry, merging hazard exposure and protective capacity into a single score and thereby masking the divergent investment logic that each dimension implies. The two-dimensional structure thus directly informs resource allocation in a way that unidimensional methods cannot.

3.4. Comparative Assessment: Hazards vs. Protection

Integrating FHI and FSI analyses reveals the asymmetry of the fire safety landscape. Table 5 highlights the top priorities in each dimension.

Table 5. Comparative analysis of FHI and FSI priority structures (equal weighting, 50/50).

Dimension	Top Priority Factors	Local Weight
FHI (Hazards)	Human factors	0.228
	Modern composite facades	0.210
	Interior finishing materials	0.207
FSI (Protection)	Intelligent systems (AI/IoT)	0.4133
	Passive protection measures	0.2113
	Fire service operational capabilities	0.1740

Under an equal weighting scenario (50/50), healthcare facilities (ZL II) emerge as the highest priority category, as shown in the "Equal" column of Table 6.

Table 6. Building category priority weights under different FHI/FSI weighting scenarios.

Building Category	Equal (50/50)	FHI-Dominant (90/10)	FSI-Dominant (10/90)
ZL II (Healthcare/Childcare)	0.26	0.22	0.31
ZL I (Public Assembly)	0.23	0.21	0.24
ZL V (Collective Residential)	0.21	0.21	0.21
ZL IV (Multi-family Residential)	0.13	0.13	0.09
ZL III (Office/Administrative)	0.12	0.12	0.10
PM (Production/Warehouse)	0.10	0.10	0.06

3.5. Impact of Hierarchical Weighting on Building Category Priorities

Extreme weighting scenarios reveal two contrasting phenomena. As shown in Figure 3, hazard-focused assessment (FHI-dominant) yields convergent priorities, whereas protection-focused assessment (FSI-dominant) yields divergent priorities.

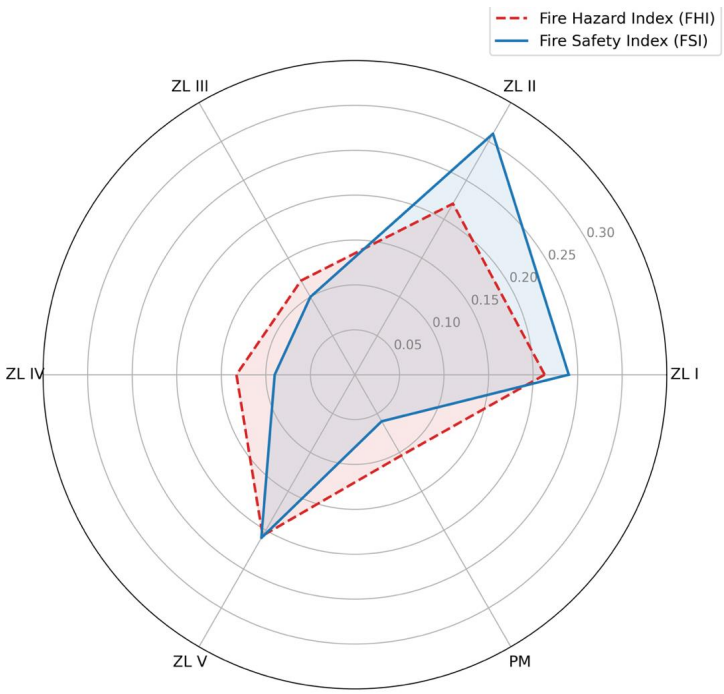


Figure 3. FHI vs. FSI comparison radar chart by building category showing relative priorities for hazards and safety measures across all building types.

When hazards are emphasized Figure 4 (90/10), the priority span is narrow (0.116), suggesting universal mitigation needs. When protection is emphasized (10/90), the span more than doubles (0.250), with ZL II facilities separating significantly from other categories (0.310), indicating a need for targeted investment.

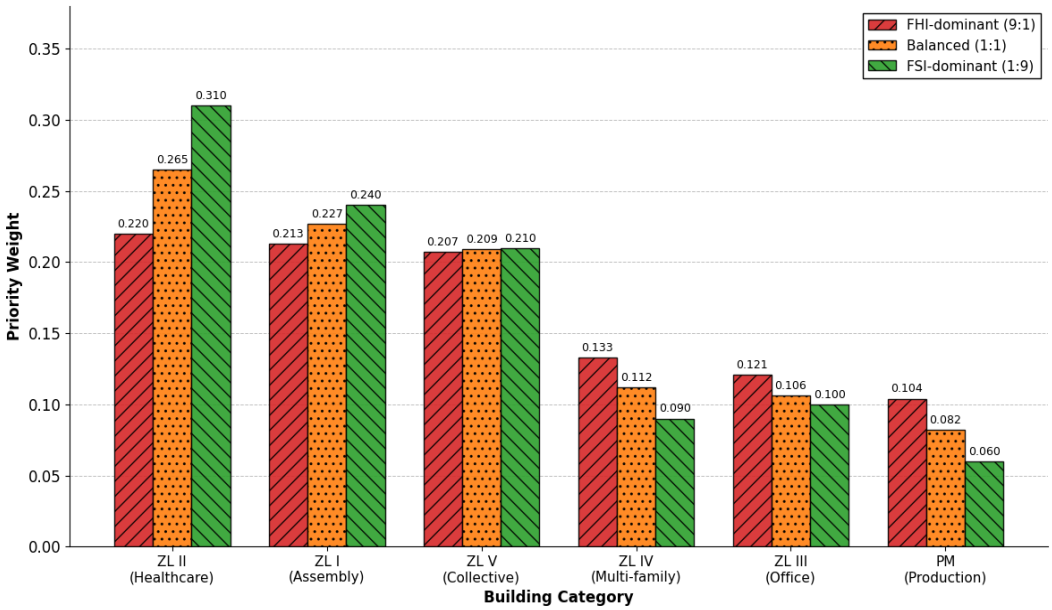


Figure 4. Sensitivity analysis showing building category priority weights under three weighting scenarios: FHI-dominant (9:1), balanced (1:1), and FSI-dominant (1:9).

3.6. Sensitivity Analysis and Strategic Implications

Figure 5 visualizes the risk–protection balance, showing that ZL II facilities occupy the most challenging position (high hazard, high protection need).

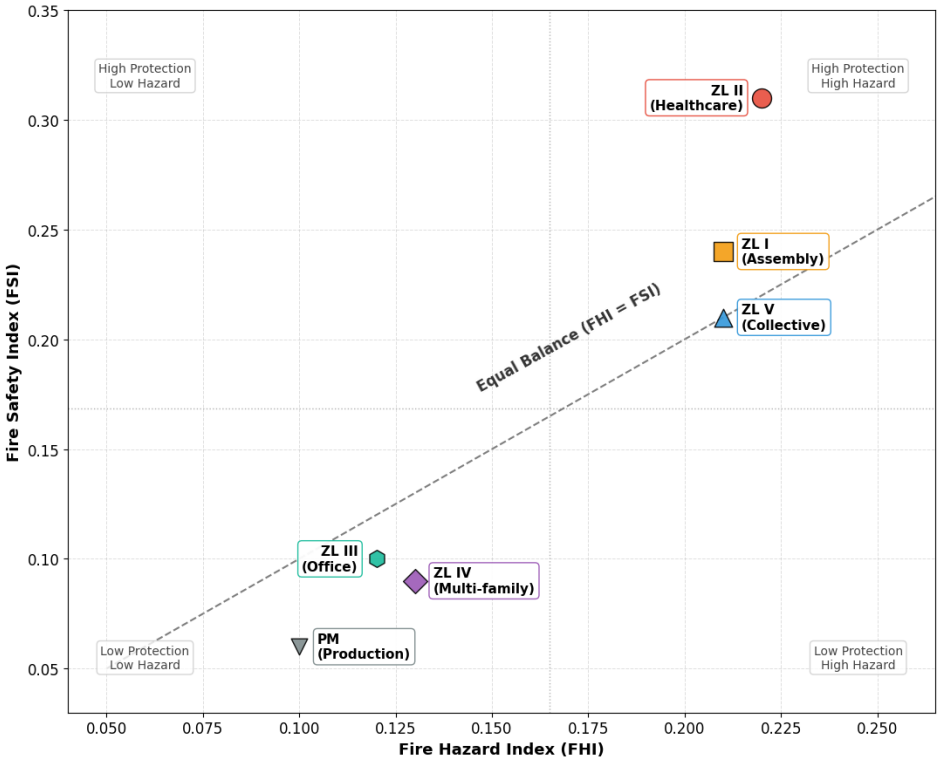


Figure 5. Scatter plot showing the relationship between Fire Hazard Index and Fire Safety Index for all building categories, illustrating risk–protection balance.

The analysis confirms that strategic orientation fundamentally shapes resource allocation. Risk-averse policies should adopt protection-dominant strategies concentrating resources on vulnerable populations (ZL II), while cost-conscious strategies should emphasize universal hazard mitigation.

4. Discussion

4.1. Principal Findings in Context

This study developed and validated a comprehensive fire safety assessment model for Polish buildings using the Analytic Hierarchy Process, establishing four principal findings with significant theoretical and practical implications. First, human factors (0.228) and combustible building materials (facades 0.210, interior finishes 0.207) dominate fire hazards, while intelligent AI/IoT systems (0.4133) and passive protection measures (0.2113) offer the greatest safety enhancement potential. Second, fire safety assessment requires fundamentally two-dimensional analysis—hazard identification and protection evaluation—with neither dimension substitutable for the other. Third, hazard-focused assessment produces convergent building category priorities (span 0.116), suggesting universal intervention needs, while protection-focused assessment yields divergent priorities (span 0.250), indicating targeted investment opportunities. Fourth, strategic orientation operationalized through FHI/FSI weighting fundamentally shapes resource allocation frameworks, enabling explicit policy choices regarding intervention emphasis.

The dominance of human factors aligns with international fire statistics demonstrating that human error accounts for 60–80% of fire incidents across developed nations [2,28]. However, the magnitude of expert consensus (22.8% of total hazard weight) and its decisive lead over technical systems represents a notable departure from the engineering-focused fire safety literature, which has historically emphasized physical and technical controls over behavioral interventions [5,30]. Recent studies continue to emphasize human behavior as the critical variable in fire safety outcomes [31], with Cantizano et al. [32] demonstrating human factors' primacy in urban fire spread models and Soltanzadeh et al. [33] showing that optimal building design must accommodate human behavioral patterns rather than presuming ideal occupant response. This recognition has spurred the development of advanced training interventions, including augmented reality systems [34] and VR-based knowledge-driven evacuation platforms [35], though widespread implementation remains limited due to technological complexity and deployment costs.

The prioritization of combustible facade systems (0.210) reflects recent global awareness following high-profile incidents [6,7], with comprehensive reviews [36] documenting incident patterns across jurisdictions and recent experimental studies establishing fire performance principles for external wall systems, including wooden materials in multi-story buildings [18,37]. The near-equivalence assigned to interior finishing materials (0.207) complements the growing evidence that thermal insulation materials pose comparable hazards [38,39], though regulatory attention has disproportionately focused on facades following Grenfell [40]. Multi-criteria assessment frameworks [26] specifically targeting facade fire risk have emerged, demonstrating methodological convergence toward systematic evaluation approaches paralleling this study's AHP methodology. Recent advances in non-combustible cladding alternatives [41] and fire-retardant coatings [42,43] offer technical solutions, though widespread retrofit implementation faces economic barriers, particularly in existing building stocks. Various multi-criteria approaches to fire risk assessment in large-scale commercial and high-rise buildings, including intuitionistic fuzzy and social graph methods [44], further confirm the complexity of such evaluations.

The FSI finding regarding intelligent systems' exceptional priority (41.33%) represents the most striking departure from the existing literature. While recent studies acknowledge

AI/DT/IoT's potential in fire safety [20,22,45], none have documented expert assessment assigning such dominant weight to emerging technologies relative to established protection approaches. The magnitude reflects expert opinion—rather than empirically validated deployment outcomes—that AI/IoT systems hold the transformative potential to address the dominant hazard (human factors) through automated decision support, real-time monitoring, and adaptive evacuation guidance [35]. Recent feasibility demonstrations integrating BIM with multi-stakeholder fire risk models [19] and machine learning-based building reconstruction for evacuation assessment [46] are promising, yet large-scale deployment data confirming the anticipated benefits at an acceptable cost remain scarce. This priority therefore represents anticipated future potential rather than current prevalence and should be interpreted with appropriate caution: if implementation barriers (high initial costs, integration complexity, cybersecurity concerns, limited professional expertise) prove more persistent than expected, the priority structure would require revision. The framework's sensitivity analysis mechanism enables such recalibration as deployment evidence accumulates. Recent AHP-based assessments of polyurethane foam fire hazard using entropy-weighted TOPSIS also confirm the high risk associated with certain insulation materials [47].

The convergence–divergence phenomenon documented in Section 3.5 constitutes a novel contribution to fire safety assessment methodology. Existing AHP applications in fire safety [11–16] have focused on establishing priority rankings but have not systematically examined how different strategic emphases alter the distribution of those priorities. The finding that hazard-focused analysis produces convergent priorities while protection-focused analysis yields divergent priorities has not been previously documented in the fire safety literature. This asymmetry has immediate practical significance: it demonstrates that "one-size-fits-all" approaches are appropriate for hazard mitigation (all building types present similar hazard profiles) but inappropriate for protection investment (building types vary dramatically in their capacity to benefit from enhanced protection). The convergence–divergence framework therefore provides a theoretical foundation for differentiated fire safety policies combining universal hazard reduction with targeted protection enhancement.

The two-dimensional framework established through comparative FHI-FSI analysis advances fire safety assessment beyond unidimensional risk scoring approaches. Traditional fire risk assessment methodologies typically aggregate hazards and protections into single risk indices [12,13], obscuring the fundamental distinction between sources of risk and capacity to manage risk. By maintaining analytical separation between hazards (FHI) and protections (FSI) while enabling their integration through weighted synthesis, the framework reveals insights unavailable through aggregated approaches: that the most significant hazards (human factors, combustible materials) are precisely those most difficult to control; that the most effective protections (intelligent systems) face the greatest implementation barriers; and that optimal safety strategies require simultaneous progress in both dimensions rather than sequential or substitutive efforts.

Positioning these findings within the Polish context reveals both consistency with international patterns and distinctive characteristics. The minimal weight assigned to electrical installations (0.039) and gas systems (0.095)—combined with experts' explicit recognition of rigorous PN-EN standards and mandatory inspection regimes—suggests that Poland has successfully implemented technical system regulation. This represents a success story: comprehensive standards, professional certification requirements, and enforcement mechanisms have effectively mitigated technical hazards that remain problematic in jurisdictions with weaker regulatory frameworks. However, the dominance of unregulated or weakly regulated hazards (human behavior, material combustibility)

indicates that further progress requires moving beyond technical system oversight into domains less amenable to traditional engineering controls—behavioral science, material science, organizational management, and educational systems.

The findings validate and extend performance-based design frameworks advocated by SFPE and codified in ISO 23932-1 [48]. Performance-based approaches establish safety objectives (successful evacuation within available safe egress time, structural stability during firefighting operations) and permit flexible means of achievement, contrasting with prescriptive codes specifying required technical systems. The AHP framework developed here operationalizes performance-based principles by quantifying the relationships between hazards, protections, and building categories, enabling designers and regulators to evaluate whether proposed protection strategies adequately address identified hazards for specific building types. The convergence–divergence finding particularly supports performance-based philosophy: it demonstrates that, while hazard management requires universal baseline measures (consistent with prescriptive minima), protection optimization demands building-specific analysis (consistent with performance-based flexibility). The framework therefore bridges prescriptive and performance-based approaches, establishing a transparent methodology for graduated requirements calibrated to building category priorities under relevant strategic emphasis.

4.2. Theoretical Implications

The convergence–divergence phenomenon documented in this study has significant theoretical implications for understanding fire safety as a complex socio-technical system. The convergence of hazard priorities across building categories indicates that fire risk is an emergent property of human occupancy itself rather than a characteristic differentiating building types. All occupied buildings contain human behavioral uncertainty (knowledge deficits, procedural non-compliance, panic potential), combustible materials (furnishings, finishes, stored goods), and ignition sources (electrical equipment, cooking appliances, heating systems). The specific configurations vary—healthcare facilities house vulnerable populations requiring extended evacuation time, public assembly buildings accommodate unfamiliar users in complex layouts, and residential buildings contain sleeping occupants with delayed detection—but the fundamental hazard components remain consistent. This universality explains why hazard reduction strategies (education, material restrictions, behavioral protocols) must be applied broadly rather than concentrated on specific building types.

Conversely, the divergence of protection priorities reveals that buildings vary dramatically in their capacity to benefit from enhanced protective investment. This variation stems from three factors: population vulnerability (healthcare facilities housing mobility-impaired individuals derive a greater benefit from intelligent evacuation systems than office buildings with able-bodied workers); architectural complexity (multi-story buildings with intricate layouts benefit more from dynamic wayfinding than single-story structures with simple egress); and operational constraints (24 h facilities like hospitals require more robust detection and suppression than facilities with defined operating hours). The divergence therefore reflects not differences in inherent risk but differences in protection efficacy—how much additional safety can be achieved through technological investment.

This asymmetry between convergent hazards and divergent protection needs challenges the equilibrium assumptions underlying some fire safety frameworks. If hazards and protection requirements both converged, optimal resource allocation would distribute investment proportionally across all building categories. If both diverged consistently (high-hazard buildings also requiring maximum protection), resource concentration would be straightforward. However, the observed pattern—convergent hazards, diver-

gent protection—creates optimization complexity: universal hazard mitigation establishes baseline safety across all buildings, while targeted protection investment amplifies safety in categories where technology can compensate most effectively for residual risk. The implication is that fire safety advancement requires portfolio strategies balancing broad-based hazard reduction with concentrated protection enhancement rather than uniform investment across interventions and building types.

The two-dimensional FHI-FSI framework advances fire safety theory by decomposing the unitary concept of "fire risk" into constituent components with distinct characteristics and policy implications. Traditional risk frameworks treat hazards and controls as opposing forces along a single continuum, where enhanced controls simply reduce risk magnitude [12,13]. The two-dimensional approach recognizes fundamental differences: hazards are largely exogenous to fire safety interventions (human behavior, material properties, occupancy patterns exist for reasons unrelated to fire safety and resist modification), while protections are endogenous (designed explicitly for fire safety purposes and amenable to technological improvement). This distinction matters because it suggests different intervention logics: hazard management requires working within the constraints imposed by building function and user behavior, while protection optimization can pursue technological frontiers without functional constraints.

Recent AHP applications in fire safety demonstrate methodological diversification beyond simple priority ranking. Ding et al. [46] integrated AHP with text mining for heritage building assessment, enabling a systematic incorporation of qualitative documentation alongside expert judgment. Kee et al. [15] applied AHP specifically to 20th-century mountainous built heritage, demonstrating a context-specific adaptation of the methodology. Hybrid approaches combining AHP with entropy weighting and TOPSIS [49] or neutrosophic-AHP with fuzzy inference systems [50] suggest that AHP increasingly serves as a component within multi-method frameworks rather than a standalone technique. This methodological evolution parallels our integration of AHP with systematic sensitivity analysis, though our emphasis on convergence–divergence patterns through weight variation represents a novel analytical direction not documented in the existing AHP fire safety literature. The convergence–divergence finding particularly advances AHP application by demonstrating that strategic weight variation can reveal the structural properties of decision problems—such as the differential distribution of hazards versus protections—invisible in single-weighting scenarios.

The framework also illuminates why "defense in depth" strategies prove effective in fire safety. Defense in depth—employing multiple independent protection layers—succeeds precisely because protections are not substitutes but complements addressing different aspects of hazard exposure [27]. Passive compartmentation limits fire spread but cannot prevent ignition; active detection enables early response but requires functional suppression systems; intelligent evacuation guidance optimizes egress but presumes an adequate structural fire resistance. Each protection layer addresses specific failure modes, and their combination provides resilience against single-point failures. The two-dimensional framework formalizes this complementarity by maintaining an analytical distinction between hazard sources requiring management and protection capabilities providing defense.

The study also contributes methodologically to AHP application in complex socio-technical systems. Most AHP applications establish priority rankings and terminate analysis [11–16], treating weights as fixed parameters rather than strategic variables. By systematically varying FHI/FSI weighting ratios and examining the consequences for building category priorities, this study demonstrates how AHP can transition from a descriptive tool (what are the priorities?) to a prescriptive framework (how do priorities change under different strategic orientations?). The sensitivity analysis reveals that AHP methodology can

illuminate the structural properties of decision problems—such as convergence–divergence patterns—that remain invisible in single-weighting scenarios. This approach has a broad applicability beyond fire safety to any multi-criteria decision context where strategic orientation remains contested or evolving.

The finding that strategic orientation fundamentally shapes resource allocation outcomes validates stakeholder engagement in fire safety policymaking. If priorities were invariant to strategic emphasis, expert technical analysis alone could determine optimal interventions. However, the demonstrated malleability—ZL II priority ranging from 0.220 to 0.310 depending on FHI/FSI weighting—indicates that technical analysis cannot prescribe solutions independent of strategic values. The appropriate balance between hazard reduction and protection investment reflects societal risk tolerance, resource availability, political feasibility, and philosophical commitments regarding individual versus collective responsibility for safety. The AHP framework does not resolve these normative questions but provides a transparent methodology for exploring implications of alternative answers, enabling evidence-based policy deliberation regarding trade-offs that ultimately reflect values rather than purely technical considerations.

Finally, the study contributes to understanding temporal dynamics in fire safety priorities. The dominance of intelligent AI/IoT systems (41.33%) despite minimal current deployment suggests that expert assessment focuses on anticipated future states rather than existing conditions. This forward-looking orientation contrasts with retrospective approaches emphasizing historical incident data [25,26]. The temporal dimension matters because fire safety systems have decade-scale lifespans—buildings designed today will operate for 50+ years with incremental technology updates. Expert judgment incorporating anticipated technological maturation therefore provides more relevant guidance for contemporary design decisions than historical statistics reflecting obsolete building stocks and bygone technologies. However, this forward orientation also introduces uncertainty: if anticipated AI/IoT capabilities fail to materialize at expected cost-effectiveness, the priority structure would require revision. The framework's flexibility in weight adjustment enables such recalibration as technological trajectories become clearer.

4.3. Policy and Practice Implications

The findings generate actionable recommendations across multiple domains of fire safety policy and practice. These implications are organized by stakeholder group—regulatory authorities, building owners and managers, design professionals, and technology developers—recognizing that effective fire safety improvement requires coordinated action across the entire building lifecycle from code development through design, construction, operation, and periodic upgrade.

For regulatory authorities and code developers, the convergence–divergence finding suggests that building codes should combine universal prescriptive requirements (addressing convergent hazards) with graduated performance-based provisions (addressing divergent protection needs). Universal requirements should focus on hazard limitation: restricting combustible materials in critical applications (facades, egress routes, high-occupancy spaces), mandating occupant fire safety education programs, establishing behavioral protocols for high-risk activities, and requiring periodic hazard audits. These measures address the factors ranked highest in FHI analysis and apply across all building categories given hazard convergence. The Polish regulatory framework already implements comprehensive technical system requirements (electrical and gas installations), explaining their minimal FHI weights; extending this regulatory success to materials and human factors represents the logical next frontier.

Graduated performance-based provisions should address protection system deployment, recognizing that buildings vary dramatically in their capacity to benefit from enhanced investment. The three strategic regimes identified in Section 3.6 provide operational guidance: healthcare facilities (ZL II), public assembly buildings (ZL I), and collective residential structures (ZL V) warrant enhanced protection requirements beyond baseline code minima, particularly regarding intelligent detection and evacuation systems. These requirements could be implemented through tiered compliance paths, basic prescriptive compliance for lower-priority categories (ZL III, ZL IV, PM) versus enhanced performance-based compliance for high-priority categories, demonstrating through quantitative analysis (egress modeling, fire dynamics simulation, risk assessment) that the proposed protection strategies achieve the specified safety objectives for vulnerable populations or complex architectural conditions.

The dominance of intelligent systems in FSI analysis (41.33%) suggests that regulatory frameworks should actively facilitate AI/IoT technology adoption rather than merely permitting it. The current building codes in Poland and internationally were largely developed before the widespread availability of intelligent building systems and therefore lack provisions explicitly recognizing their capabilities [48]. Regulatory updates should: establish performance standards for intelligent detection networks (sensor density, false alarm rates, response times); define requirements for dynamic evacuation guidance systems (information accuracy, update frequency, accessibility for diverse populations); specify integration protocols between building systems and emergency responder networks; and create certification processes for AI-based predictive risk analytics. These provisions would reduce the regulatory uncertainty currently inhibiting intelligent system deployment, addressing the implementation barrier identified in Section 3.3.

For building owners and facility managers, the findings provide an evidence-based prioritization framework for fire safety investments. Buildings positioning high on both FHI and FSI dimensions (healthcare facilities, public assembly structures) require comprehensive strategies addressing both hazard management and protection enhancement. Investments should prioritize: intelligent evacuation systems with occupancy tracking and dynamic route optimization; comprehensive passive compartmentation with fire-rated construction and protected egress; staff training programs emphasizing behavioral protocols and emergency response procedures; and regular coordination exercises with local fire brigades ensuring familiarity with the building layout and operational constraints. The 0.310 priority weight for ZL II facilities under protection-dominant weighting (Section 3.5) suggests that healthcare and childcare facility operators should allocate 25–30% of institutional fire safety budgets to protective technologies, with the remaining resources directed toward education, training, and procedural compliance.

The healthcare facility fire safety priorities identified in this study (ZL II: 0.310 under FSI-dominant weighting, 0.265 under balanced weighting) align with specialized assessment frameworks [50] recognizing that hospitals, nursing homes, and childcare centers require enhanced protection beyond standard building categories due to vulnerable populations (elderly, children, mobility-impaired individuals) and 24 h occupancy patterns. The substantial priority differential between healthcare facilities and other categories under protection-focused strategy suggests that regulatory frameworks should establish dedicated healthcare fire safety standards rather than treating hospitals as generic institutional occupancies. Investment priorities should emphasize intelligent evacuation systems with real-time occupancy tracking, staff training programs addressing cognitive load during emergencies, and coordination protocols with emergency medical services ensuring the continuity of patient care during evacuation scenarios.

Buildings in lower-priority categories can achieve adequate safety through baseline compliance with universal hazard mitigation requirements plus standard active protection systems. The convergence finding indicates that hazard management—occupant education, material selection, and procedural discipline—provides a similar marginal benefit across all building types and should receive consistent attention regardless of category. However, the divergence finding suggests that advanced protection technologies yield limited marginal benefit in simpler buildings with able-bodied occupants, indicating that investment beyond code-minimum active systems may not be cost-effective. The resources saved through avoiding unnecessary protection enhancement can be redirected toward hazard management programs delivering universal benefit.

For architectural and engineering design professionals, the two-dimensional framework suggests integrated design approaches considering hazards and protections simultaneously rather than sequentially. Traditional design workflows often address fire safety reactively—designing buildings for functional and aesthetic objectives, then adding fire protection systems to achieve code compliance [5,30]. The framework supports proactive integration: evaluating how architectural decisions (material selection, spatial organization, circulation patterns) influence both hazard exposure and protection efficacy, then optimizing protection strategies to address residual risks after hazard minimization through design. For example, intelligent evacuation systems (FSI priority) deliver maximum value in buildings where architectural complexity creates wayfinding challenges (FHI factor), suggesting that designers should either simplify layouts to reduce wayfinding difficulty or invest in advanced guidance systems to compensate for complexity—but not ignore the hazard–protection interaction.

The dominance of passive protection in FSI analysis (21.13%, second only to intelligent systems) validates the continued emphasis on fire-resistant construction, compartmentation, and protected egress despite technological advances. Passive measures provide a "last line of defense" when active and intelligent systems fail, malfunction, or face conditions exceeding design parameters. Design professionals should resist the temptation to reduce passive protection investment based on confidence in active/intelligent systems; rather, passive measures establish foundational safety enabling active/intelligent systems to optimize performance. This complementarity suggests design strategies layering protection types: passive compartmentation limits fire spread, active detection enables early response, intelligent systems optimize evacuation, and fire service access ensures external intervention capability—each layer addressing different failure modes and collectively providing defense in depth.

Contemporary performance-based fire safety engineering increasingly incorporates computational fluid dynamics with validated tenability criteria [51], enabling the quantitative assessment of smoke spread, temperature profiles, and toxic gas concentrations beyond prescriptive code compliance. This analytical capability supports the protection-focused investment strategies identified through FSI analysis, as performance-based methods can demonstrate how intelligent detection systems and passive compartmentation interact synergistically to achieve safety objectives. Recent advances in evacuation modeling [52,53] incorporating human behavioral patterns enable designers to evaluate alternative protection strategies under realistic occupant response scenarios, addressing the human factors hazard identified as dominant in FHI analysis. The integration of serious gaming and BIM-based simulation [54] facilitates stakeholder engagement during design development, enabling building owners and operators to understand fire safety trade-offs through interactive visualization rather than abstract engineering calculations.

For technology developers and system integrators, the findings identify market opportunities and performance priorities for intelligent fire safety systems. The 41.33% FSI weight

indicates substantial expert confidence in AI/IoT potential, suggesting that manufacturers investing in product development can anticipate regulatory support and market demand as stakeholders recognize technology value. Priority development areas should include: real-time occupancy tracking systems using IoT sensors to inform evacuation routing (addressing the human factor hazard by compensating for behavioral uncertainty); predictive maintenance analytics identifying degradation in passive and active protection before failures occur (extending asset life while maintaining reliability); BIM and GIS integration [19] enabling multi-stakeholder coordination and pre-incident planning (addressing fire service operational capabilities); and machine learning-based reconstruction systems [46] supporting evacuation assessment under emergency conditions. Recent frameworks explicitly linking fire safety with sustainability objectives [55] demonstrate that intelligent systems can serve dual purposes—enhancing safety while reducing environmental impact through optimized resource deployment and lifecycle assessment of protection systems [56]. Digital twin technologies enable virtual prototyping and system optimization prior to physical implementation, reducing deployment risks and facilitating stakeholder buy-in through a visualization of anticipated benefits.

However, technology developers should recognize that deployment success requires addressing the non-technical barriers identified in Section 3.3: high initial costs, integration complexity with legacy systems, cybersecurity concerns, and limited professional expertise. Solutions should emphasize: modular architectures enabling incremental deployment rather than requiring comprehensive building retrofits; open communication protocols facilitating integration across manufacturers; cybersecurity-by-design protecting against malicious actors exploiting building systems; and intuitive interfaces reducing training requirements for facility staff. Technology adoption will be paced not by performance capabilities but by addressing these implementation barriers, suggesting that successful products balance technical sophistication with deployment pragmatism.

Finally, for fire service organizations, the findings validate the importance of pre-incident planning and building familiarization. The 17.40% FSI weight assigned to fire service operational capabilities indicates expert consensus that even the most sophisticated building protection systems require effective external intervention for major incidents. Fire departments should prioritize: regular inspection and familiarization exercises in high-priority buildings (ZL II, ZL I, ZL V), ensuring that responders understand layouts, protection systems, and vulnerable populations; coordination protocols with facility management establishing communication procedures during emergencies; access infrastructure maintenance (hydrants, apparatus approach routes, connection points); and training specific to intelligent building system interfaces, enabling responders to access real-time building data (occupancy locations, fire progression, system status) supporting tactical decision-making. The integration between intelligent building systems and fire service operations represents a frontier requiring organizational adaptation—responders accustomed to operating with limited building information will need training to effectively utilize data streams from advanced monitoring networks.

4.4. Methodological Contributions and Limitations

The study demonstrates AHP methodology's effectiveness for fire safety assessment while acknowledging inherent limitations requiring careful interpretation. AHP's primary strength lies in structuring complex, multi-dimensional decision problems into hierarchical frameworks, enabling systematic evaluation through pairwise comparisons [12]. For fire safety—characterized by numerous interacting factors, competing priorities, and stakeholder disagreement regarding relative importance—AHP provides a transparent methodology for synthesizing expert judgment into quantitative priority weights. The con-

sistency ratio validation (CR < 0.08 for all matrices) confirms judgment reliability, indicating that expert assessments reflect coherent understanding rather than random preferences.

The expert panel composition—combining fire safety inspectors, fire service officers, and architects—ensured multi-perspective representation spanning regulatory compliance, operational response, and design integration. This diversity strengthens findings by capturing complementary knowledge domains rather than single-discipline perspectives that might overemphasize specific concerns. The Aggregation of Individual Judgments (AIJ) approach using geometric mean synthesis preserved individual perspectives while deriving group consensus, avoiding domination by vocal participants that can occur in consensus-building workshops [28,29]. Recent applications combining the Delphi method with AHP for expert elicitation [50] validate the structured pairwise comparison approach employed here, though our single-round methodology sacrificed iterative refinement for the preservation of independent judgment. This trade-off—preserving authenticity versus achieving refined consensus—reflects a methodological choice appropriate for exploratory pilot studies establishing baseline priorities, though future research with larger panels could employ Delphi iterations to examine whether expert judgments converge or diverge after viewing group patterns. The resulting weights therefore represent an authentic expert consensus grounded in professional knowledge and experience rather than methodological artifacts or data quality issues.

However, several methodological limitations warrant acknowledgment. First, the expert panel comprised ten participants, which, while adequate for pilot validation, represents a modest sample size limiting statistical power for subgroup analysis. Larger panels (20–30 experts) would enable an examination of whether priorities differ systematically across professional roles (inspectors versus fire service versus architects) or experience levels. The current findings reflect consensus across the panel but cannot identify whether specific subgroups hold divergent views. Future research should expand the panel size and examine whether priority structures vary by expert characteristics.

Second, the study employed single-round elicitation without iterative feedback. Delphi-style approaches conducting multiple rounds with anonymous feedback enable experts to reconsider initial judgments after viewing group patterns, potentially improving consensus and reducing outlier assessments [28]. However, Delphi requires a substantial time commitment from participants and risks convergence artifacts where experts conform to perceived group opinion rather than maintaining independent judgment. The single-round approach prioritized preserving authentic expert perspectives over iterative refinement, accepting the potential tradeoff between initial judgment preservation and refined consensus.

Third, the pairwise comparison methodology, while reducing cognitive load relative to absolute rating scales, still requires numerous judgments—experts completed matrices totaling 78 pairwise comparisons across FHI subcriteria, FSI subcriteria, and building category evaluations. Judgment fatigue may influence later comparisons, potentially introducing systematic bias. The study mitigated this concern through limiting total comparison requirements to feasible levels (78 comparisons completable within 90 min sessions), randomizing matrix presentation order across experts to distribute fatigue effects, and monitoring consistency ratios to identify fatigued or disengaged participants (none identified). Nevertheless, cognitive load remains an inherent limitation of comprehensive AHP applications, suggesting that future research should explore abbreviated hierarchies focusing on highest-priority factors.

Fourth, the building category classifications (ZL I–V, PM) reflect the Polish regulatory framework, which, while appropriate for Polish application, may not translate directly to other jurisdictions with different building classification systems. International build-

ing codes use varied taxonomies (occupancy groups, use classifications, risk categories) that do not map precisely to Polish designations. The convergence–divergence finding and two-dimensional framework represent generalizable contributions transcending specific classification schemes, but the absolute priority weights for particular building types remain Polish-specific. Cross-national validation would establish whether the convergence–divergence pattern persists across jurisdictions or reflects Polish-specific conditions. Users applying this framework outside Poland should therefore treat the specific weights presented here as illustrative rather than directly transferable and should replicate the expert elicitation process with professionals embedded in the relevant national regulatory context before drawing policy conclusions.

Fifth, the study employed equal weighting between FHI and FSI in the baseline analysis (Section 3.4), then explored extreme weightings in the sensitivity analysis (Section 3.5). This approach establishes bounds (convergence under FHI emphasis, divergence under FSI emphasis) but does not determine the optimal weighting for specific policy contexts. The "correct" FHI/FSI balance depends on stakeholder values, resource constraints, political feasibility, and risk tolerance—factors extending beyond technical analysis. The framework enables exploring implications of alternative weightings but cannot prescribe which weighting is objectively superior. Future research integrating AHP with decision analysis approaches (multi-attribute utility theory, cost–benefit analysis) could link technical priorities to economic optimization, though such approaches introduce additional assumptions regarding value trade-offs.

Sixth, expert assessments reflect anticipated future states (particularly for intelligent systems) rather than purely current conditions. This forward-looking orientation aligns with design decision timeframes (buildings designed today will operate for decades) but introduces uncertainty regarding whether anticipated capabilities will materialize. The 41.33% weight for intelligent systems presumes that AI/IoT technologies will mature to deliver predicted safety benefits at acceptable costs—assumptions that remain unvalidated in large-scale deployments. If technological development disappoints or implementation barriers prove insurmountable, priority weights would require revision. The framework's flexibility enables such recalibration, but users should recognize that current weights incorporate optimistic technology forecasts.

Seventh, the study focuses on fire initiation and propagation hazards plus protective system capabilities but does not explicitly address post-fire resilience—building recovery, business continuity, environmental impact of fire suppression water, or long-term community effects. Sustainable fire safety increasingly emphasizes not only preventing casualties and property damage but also minimizing disruption and facilitating rapid recovery [27]. Future framework iterations should incorporate resilience metrics alongside traditional safety measures, recognizing that fire safety contributes to broader sustainability objectives beyond immediate life safety.

Eighth, the AHP analysis treats subcriteria as independent despite potential interactions. For example, intelligent evacuation systems' effectiveness depends partly on passive compartmentation maintaining tenable egress conditions, yet the framework evaluates these protection elements separately. The Analytical Hierarchy Process methodology assumes independence among alternatives and criteria [12], which simplifies analysis but may not capture synergistic or antagonistic interactions. Network analysis approaches (Analytical Network Process) accommodate interdependencies but substantially increase complexity. The independence assumption represents reasonable approximation for priority assessment, though detailed implementation planning should consider interaction effects.

Finally, the study validates the framework through expert assessment rather than empirical outcome data. Validating fire safety interventions through actual fire incident

analysis faces substantial challenges: major fires remain relatively rare events (fortunately), making statistical analysis difficult; confounding factors (building age, occupant characteristics, weather conditions) complicate attribution; and ethical constraints prevent controlled experimentation. Expert judgment represents an appropriate validation methodology for low-frequency, high-consequence events where empirical data remain sparse. This limitation is particularly relevant for intelligent AI/IoT systems, whose 41.33% FSI weight is based entirely on expert opinion about anticipated future capabilities rather than evidence from existing deployments. External validation against empirical fire incident databases—or, where available, against building-level outcome data from jurisdictions with a higher AI/IoT penetration—should be prioritized in subsequent research. However, as intelligent fire protection systems achieve wider deployment, longitudinal studies comparing predicted benefits (expert assessments) against realized outcomes (incident data) would provide empirical validation currently unavailable.

Despite these limitations, the study establishes a robust methodological foundation for fire safety assessment in Polish buildings. The convergence–divergence finding demonstrates that AHP can illuminate structural properties of decision problems beyond simple priority ranking. The two-dimensional framework provides analytical architecture applicable beyond specific weights or building classifications. And the sensitivity analysis approach shows how varying strategic emphasis reveals insights unavailable in single-weighting scenarios. These methodological contributions validate AHP as a powerful tool for fire safety assessment while acknowledging boundary conditions requiring recognition in interpretation and application.

4.5. Future Research Directions

Future research should pursue five priority directions to validate and extend this framework. First, **longitudinal studies** are required to track how priority weights evolve as intelligent technologies mature and deployment data become available. Second, **economic optimization** research should couple these AHP priorities with cost–benefit analyses to identify resource allocations that maximize safety per unit of investment. Third, the anticipated benefits of AI/IoT systems must be **empirically validated** through post-occupancy evaluations, digital twin simulations, and controlled experiments to confirm expert optimism [19,46].

Additionally, **cross-national comparative research** is necessary to determine whether the "convergence–divergence" pattern is a universal property of fire safety or specific to the Polish regulatory context. Finally, the two-dimensional AHP framework should be **extended to related domains**—such as seismic safety or flood protection—where the distinction between inherent hazard exposure and protective capacity is equally critical for sustainable resilience planning.

5. Conclusions

This study developed and validated a comprehensive AHP-based fire safety assessment model for Polish buildings, yielding four principal contributions. First, the two-dimensional FHI/FSI framework demonstrates that fire safety requires simultaneous attention to hazard sources and protective capabilities—neither dimension can substitute for the other. Second, the convergence–divergence phenomenon reveals that hazard priorities converge across building types (span 0.116), supporting universal mitigation measures, while protection priorities diverge (span 0.250), justifying targeted investment. Third, human factors (0.228) and combustible materials (facades 0.210, finishes 0.207) dominate hazards, while intelligent AI/IoT systems (0.4133)—interpreted as anticipated potential rather than current prevalence—offer the greatest protective leverage. Fourth, varying the

FHI/FSI weighting explicitly reveals how strategic orientation shapes resource allocation, enabling transparent evidence-based policy deliberation.

For Polish fire safety policy, the findings suggest that regulatory frameworks should combine universal prescriptive requirements addressing convergent hazards (material restrictions, education mandates, behavioral protocols) with graduated performance-based provisions addressing divergent protection needs (intelligent systems in healthcare facilities, enhanced passive protection in public assembly buildings). The minimal weights assigned to electrical (0.039) and gas installations (0.095) validate regulatory success in technical system oversight, suggesting that further progress requires extending this rigor to currently unregulated or weakly regulated domains—human behavior, material combustibility, and intelligent technology deployment. Healthcare/childcare facilities (ZL II) warrant a disproportionate investment under protection-focused strategy (potentially 25–30% of fire safety resources), while office buildings, multi-family housing, and production facilities can achieve adequate safety through baseline compliance plus universal hazard mitigation.

The convergence–divergence framework provides a theoretical foundation for differentiated policies combining universal hazard reduction with targeted protection enhancement. The finding that "one-size-fits-all" approaches suit hazard mitigation but not protection investment has immediate practical significance for resource allocation. The dominance of human factors and combustible materials indicates that technical system regulation, while necessary, proves insufficient for comprehensive fire safety—behavioral interventions, material restrictions, and organizational management require parallel emphasis.

Five directions are recommended for future research: (1) longitudinal studies tracking how priority weights evolve as AI/IoT deployment matures; (2) economic optimization linking AHP priorities to cost-effectiveness analysis; (3) empirical validation of intelligent system benefits through post-occupancy data and controlled experiments; (4) cross-national replication to test whether the convergence–divergence pattern is universal or Poland-specific; and (5) extension of the FHI/FSI framework to analogous safety domains (seismic, flood, cyber). Together, these directions would ground the current expert-based findings in empirical evidence and broaden their applicability.

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Abbreviations

The following abbreviations are used in this manuscript:

AHP	Analytic Hierarchy Process
AI/IoT	Artificial Intelligence/Internet of Things
AIJ	Aggregation of Individual Judgments
AIP	Aggregation of Individual Priorities
BIM	Building Information Modeling
CI	Consistency Index
CR	Consistency Ratio
FHI	Fire Hazard Index
FSI	Fire Safety Index
GDPR	General Data Protection Regulation
MCDA	Multi-Criteria Decision Analysis
PBD	Performance-Based Design
PM	Production and Warehouse Facilities
RI	Random Index
SFS	State Fire Service
WT	Technical Conditions to be Met by Buildings and Their Location
ZL I	Public Assembly Buildings
ZL II	Healthcare and Childcare Facilities
ZL III	Office and Administrative Buildings
ZL IV	Multi-family Residential Buildings
ZL V	Collective Residential Buildings

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