Article

Responsive Architecture and Fire Safety: A Comparative Review of Regulatory Regimes in the USA, Asia, and the EU/UK, with Implications for Poland in the Context of BIM/DT/AI/IoT

Przemysław Konopski * , Roman Pilch , Wojciech Bonenberg

Posted Date: 27 February 2026

doi: 10.20944/preprints202602.1202.v1

Keywords: fire safety; responsive architecture; performance-based design (PBD); BIM; Digital Twin (DT); AI/IoT in buildings; regulatory systems; cybersecurity; fire alarm and building management systems

doi:10.20944/preprints202602.1202.v1

Article

Responsive Architecture and Fire Safety: A Comparative Review of Regulatory Regimes in the USA, Asia, and the EU/UK, with Implications for Poland in the Context of BIM/DT/AI/IoT

Przemysław Konopski [1,*], Roman Pilch [2] and Wojciech Bonenberg [3]

[1] Faculty of Architecture, Wroclaw University of Science and Technology, Wroclaw Poland
[2] Faculty of Architecture, Academy of Film, Art and Design, Lodz Poland
[3] Faculty of Architecture, Poznan University of Technology, Poznan Poland
* Correspondence: konopskiprzemek@gmail.com

Abstract

This article compares selected fire-safety regulatory systems in Japan, China, the United States, and the EU/UK, interpreted through the lens of responsive architecture and the implementation of digital technologies—Building Information Modeling (BIM), Digital Twins (DT), Artificial Intelligence (AI), and the Internet of Things (IoT). The study adopts a qualitative approach based on a structured review of legal acts, technical standards, public-sector reports, and scientific and professional literature, organised using a common analytical framework. First, the analysis identifies shared foundations across regimes: the primacy of life safety, mandatory detection and alarm functions, fire compartmentation, requirements for protected means of egress, and the increasing importance of documenting the operational status of protection measures [1,6]. It then contrasts key differences, including the permissibility of performance-based design (PBD), the extent to which digital documentation is formally recognised, organisational enforcement models, and approaches to cybersecurity for integrated Fire Alarm/Voice Alarm/Building Management/IoT ecosystems. Japan and selected Chinese cities combine stringent requirements with openness to dynamic solutions and urban-scale data platforms [2]. The USA relies on a decentralised, code-based ecosystem with a strong role for professional and industry bodies, while the EU/UK continue to strengthen harmonised standards and digital building registers, reinforced by lessons following the Grenfell Tower fire [3,4]. Against this background, Poland is discussed as broadly aligned in goals and baseline technical requirements, yet lagging in implementing PBD pathways, digital registers, formal BIM/DT integration, and minimum cybersecurity requirements. The proposed directions for change aim to create a more predictable regulatory and technical framework for the development of responsive architecture and dynamic fire-safety systems in Poland.

Keywords: fire safety; responsive architecture; performance-based design (PBD); BIM; Digital Twin (DT); AI/IoT in buildings; regulatory systems; cybersecurity; fire alarm and building management systems

---

1. Introduction

Fire safety is increasingly intertwined with sustainability objectives because building safety performance affects resilience, social well-being, and lifecycle resource efficiency. Severe fire events generate direct human impacts as well as substantial environmental and economic externalities, including material loss, waste streams, disruption of critical services, and long-term costs of reconstruction and compliance remediation. As a result, contemporary fire-safety governance can be interpreted as part of broader sustainability-oriented risk management—particularly when it moves

 doi:10.20944/preprints202602.1202.v1

toward lifecycle documentation, auditable maintenance, and data-driven prevention (European Commission; EN; ISO).

In this context, responsive architecture supported by BIM/DT/AI/IoT contributes to sustainability not only by improving evacuation outcomes, but also by enabling more reliable lifecycle stewardship of safety-critical assets. Digitally verifiable inspection histories, predictive maintenance, and interoperable safety information reduce "compliance decay" over time and support resilient operation of complex buildings and urban systems under stress [4,5]. Consequently, the present comparative review explicitly frames regulatory readiness for digital and responsive fire safety as a sustainability-relevant capability, closely linked to safe, inclusive, and resilient built environments.

Over recent decades, fire safety has gained exceptional importance in policy, law, and engineering practice in highly developed countries. The United States, Japan, China, the Member States of the European Union, and the United Kingdom have established extensive regulatory systems that evolve alongside technological progress, urbanisation, and growing expectations for protecting life and property. A common feature across these regimes is the primacy of life safety and the minimisation of losses caused by fire. In all systems, there is a strong emphasis on integrated early detection and warning (e.g., smoke detection and alarm systems), fire compartmentation, and ensuring safe, clearly marked evacuation routes [1,6]. Another shared requirement is formalised maintenance, periodic verification, and documentation of fire-protection system performance, alongside user training and drills [6].

A particularly visible trend in recent literature is the digitalisation of fire safety and deployment of innovative technologies—including AI, IoT, DT, and BIM—aimed at improving situational awareness, decision-making, and ultimately evacuation outcomes [7]. Such solutions not only increase the effectiveness of prevention and response, but also create new operational possibilities for responsive architecture—understood here as building behaviour that adapts in real time to changing risk conditions through data, automation, and dynamic control logic.

At the same time, international convergence is growing—especially in Europe, where harmonised standards and EU regulatory instruments support alignment of requirements for product performance classification, verification, and documentation traceability European Commission. Nevertheless, pronounced differences remain in organisational models and enforcement, reflecting local legislative traditions, technology maturity, and experiences of catastrophic events (e.g., post-Grenfell reforms in the UK) [8].

The purpose of this review is to synthesise core assumptions, solutions, and development trajectories of fire-safety systems in selected jurisdictions and identify major trends and challenges relevant to responsive architecture and BIM/DT/AI/IoT readiness. For transparency, each jurisdiction is reviewed using a unified six-part thematic structure: (1) current regulations; (2) technology development; (3) urban-planning development; (4) organisational development; (5) engineering development; and (6) legislative evolution and synthesis.

2. Background and Legal Frameworks for Fire-Safety Regulations in Japan, China, the USA, and the EU/UK

2.1. Japan

2.1.1. Current Fire-Safety Regulations

Japan's fire-protection system is distinctive within Asia due to its high level of detail and, crucially, strong enforcement in practice. Two laws play a central role: the Fire Service Act and the Building Standards Act, which together define the regulatory framework for new buildings, modernisation of existing facilities, and emergency response operations [2]. A fundamental premise is prevention: minimising the probability of fire ignition and maximising occupant safety if an incident occurs.

 doi:10.20944/preprints202602.1202.v1

Public buildings and multi-family residential buildings are generally subject to mandatory installation of automatic fire detection systems. In contemporary applications, these systems extend beyond smoke detectors to include temperature and gas sensors, and increasingly advanced environmental sensing solutions enabled by IoT and computer vision [9]. Fire signalling and warning infrastructure includes not only acoustic alarms but also voice communication and visual egress guidance, reflecting the needs of diverse user groups in major metropolitan and transport environments [9].

Japan places strong emphasis on continuous improvement. After serious incidents, expert investigations are conducted; resulting findings frequently drive regulatory updates and new guidance [2]. Particular attention is given to transport infrastructure (metro systems, tunnels, airports), where fire resistance requirements are complemented by smoke control and integration of alarms with systems managing occupant flow during evacuation [10].

Mandatory training and regular evacuation drills are institutionalised. Regulations require drills in public institutions, enterprises, and schools at least twice per year, involving building users [2]. Overall, Japan's regime reflects a long-term legislative and adaptive process prioritising life safety and operational readiness—supported by rigorous requirements, strong enforcement, and openness to digital technologies [2,9].

2.1.2. Development Directions: Technological Aspects

Technological development is a cornerstone of Japan's transformation of fire-safety systems. Contemporary practice increasingly relies on IoT-enabled multi-layer sensor networks combining smoke, gas, and temperature sensing with optical/thermal inputs, streaming to central platforms for analysis and decision support [9]. Research and practice increasingly explore AI-assisted detection and anomaly recognition to improve early warning and reduce false alarms [9,47].

A key trend is digitalisation of building management and safety governance through BIM-informed processes and integrated management systems. These enable real-time monitoring and control from unified interfaces, particularly in complex public and infrastructure assets [9]. Complementary work on evacuation algorithms indicates how decision support can improve routing and wayfinding under constrained conditions [11,12].

Integration with smart-city systems is increasingly visible: digital hazard maps, distributed sensing, and analytics support forecasting and rapid identification of ignition points at district scale [13]. Interoperability—ensuring seamless exchange between alarms, building management, and emergency services—is also becoming more central as multi-vendor ecosystems expand [13].

2.1.3. Development Directions: Urban-Planning Aspects

Urban densification and the growth of high-rise and mixed-use developments create complex fire-safety challenges. Japan's urban planning has long incorporated fire prevention through building separation, buffers, and "firebreak" discontinuities in dense fabrics [2]. Programmes for modernising older districts—often with vulnerable timber structures—aim to reduce metropolitan-scale conflagration risk [2].

City-scale digital risk mapping and smart-city governance increasingly support dynamic routing and response planning [13]. Agent-based and computational models are used to predict crowd behaviour during evacuation, especially in transport hubs and tunnels [11,14]. Urban fire safety is also increasingly framed within multi-hazard resilience strategies (earthquakes, floods), including plans for temporary shelters and safety zones [15].

2.1.4. Development Directions: Organisational Aspects

Japan combines strong state oversight with advanced training and public education. Professional fire services rely on frequent exercises, inter-agency coordination, and increasingly data-

 doi:10.20944/preprints202602.1202.v1

supported crisis management [13]. Public education includes campaigns and school programmes supporting prevention culture [2].

Building owners and facility managers have explicit duties to maintain systems, organise training, and keep records. Inspection and certification—through public agencies and accredited entities—support compliance and transparency [13]. Major incidents are investigated and translated into updated procedures, reinforcing a learning-oriented system [2].

2.1.5. Development Directions: Engineering Aspects—AI and IoT

IoT sensor networks are deployed across building types and infrastructure, monitoring smoke, temperature, gases, and other anomalies; data are transmitted to central systems for continuous monitoring [9]. AI systems process sensor and camera streams to improve detection and support decision-making in smoke-control operations and evacuation guidance [11,14]. Robotics and drones are emerging for reconnaissance and hazard localisation in high-risk zones, aligned with broader regional disaster-information management directions [13].

2.1.6. Development Directions: Legislative Aspects

Japan's legislative framework is dynamic and consistently implemented. A key trend is the move toward adaptive models shaped by digital monitoring, integrated systems, interoperability, and emerging cybersecurity concerns for connected safety ecosystems [13]. Expert committees translate scientific and operational recommendations into updates; major incidents often drive new requirements [2]. Japan also participates in regional cooperation that influences standard harmonisation and practice alignment [15].

2.2. China

2.2.1. Current Fire-Safety Regulations

China's fire-safety system is based on a multi-layered architecture of national law, technical codes, and enforcement procedures across the building life cycle. The core legal instrument is the Fire Protection Law of the People's Republic of China (amended 2021), which establishes duties for prevention, system maintenance, inspections, and training, and sets enforcement measures and penalties for non-compliance [16].

A central technical reference is GB 50016 [17], widely treated as a national baseline for compartmentation, egress, fire-resistance requirements, access for firefighting, and building services safety measures [17]. A defining characteristic is strong commissioning/acceptance: buildings typically cannot be used without verified acceptance; periodic inspections and documentation are required, with enforcement ranging from fines to suspension of use for deficiencies [16].

2.2.2. Development Directions: Technological Aspects

China's technology-driven transformation includes AI, IoT sensor networks, BIM-based information management, digital twins, and robotics/drones supporting both prevention and response [18,19,46]. IoT architectures integrate detectors, gas sensors, and cameras; data stream to central platforms where AI models support anomaly detection and false-alarm reduction [46].

Digital twins are increasingly framed as operational decision-support systems: sensor-fed models capable of tracking evolving incident conditions, evaluating evacuation scenarios, and supporting dynamic control of smoke management and signalling under real-time constraints [19]. Drones and robotics expand situational awareness where conditions are unsafe for responders [20].

2.2.3. Development Directions: Urban-Planning Aspects

Rapid urbanisation and high-rise growth introduce city-scale challenges. Research emphasises spatial analytics for risk mapping, hotspot identification, and response-time optimisation, especially for high-rise clusters [10,21]. Planning approaches include fire-station siting and route optimisation through multi-criteria spatial models [21]. District-scale platforms and, in more advanced cases, digital twins support simulation of evacuation and resource deployment under time pressure [19,21].

2.2.4. Development Directions: Organisational Aspects

Fire-safety performance depends on professional education, continuous training, and public awareness. Scenario-based and simulation-supported exercises improve coordination and enable evaluation of procedures under realistic constraints [20]. A critical challenge is integrating rapidly evolving technologies into daily facility management routines—ensuring systems are maintained, auditable, and operationally meaningful rather than "formal" installations [18].

2.2.5. Development Directions: Engineering Aspects—AI, IoT, BIM, and Digital Twins

China increasingly adopts PBD in complex buildings and venues, relying on numerical simulation and evidence-based justification of tenability and egress performance [19,22]. AI/IoT systems function as a "cognitive layer" interpreting sensor streams and supporting dynamic decisions such as evacuation sequencing and smoke-control logic [46]. Digital twins and analytics support both pre-occupancy testing and operational control, including anomaly detection and identification of critical points [18,19].

2.2.6. Development Directions: Legislative Aspects

Legislation is anchored in national law and supported by technical codes such as GB 50016. Policy and practice increasingly emphasise digital oversight: digitised inspection records, central platforms for traceability, and expectations that integrated systems remain testable and auditable across the building life cycle [16–18].

2.3. United States

2.3.1. Current Fire-Safety Regulations

The US operates a complex regulatory ecosystem because there is no single federal building and fire code nationwide. Requirements become enforceable through state and local adoption of model codes and referenced standards, resulting in jurisdictional variability while maintaining shared baselines [23]. Dominant producers include the International Code Council (ICC) (e.g., IBC, IFC) and the National Fire Protection Association (NFPA) (e.g., NFPA 1, NFPA 101) [24,25].

Across jurisdictions, rules typically cover fire-resistance performance and compartmentation, egress, detection/alarm/suppression systems, and inspection/testing/maintenance regimes, but thresholds and enforcement depend on local adoption and capacity [23]. Wildfire risk, especially in the wildland–urban interface, increasingly shapes policy and technology directions [26].

2.3.2. Development Directions: Technological Aspects

US trends emphasise AI-enabled decision support and multi-source data fusion for commanders and responders [27]. Policy discussions highlight cyber-physical risks: fail-safe modes, separation of IT/OT networks, access control, and continuous monitoring are emphasised because compromised systems may degrade life-safety performance [28]. In wildfire contexts, satellite and airborne imagery, cameras, drones, and sensing combined with predictive models can improve detection and response, though constraints persist regarding coverage, latency, and data management [26,29].

2.3.3. Development Directions: Urban-Planning Aspects

Suburban expansion into WUI areas links land-use planning to evacuation feasibility, emergency access, and infrastructure robustness [26]. Planning approaches emphasise defensible space, road network redundancy, evacuation capacity, siting of critical infrastructure, and GIS-based risk mapping integrated into resilience planning [28,30].

2.3.4. Development Directions: Organisational Aspects

The system is multi-layered: federal guidance, state/local authorities, professional associations, academia, and private-sector actors. This supports experimentation but also creates barriers to uniform deployment of advanced technologies, as procurement and workforce capability vary across jurisdictions [23,27]. AI adoption raises governance questions about validation, accountability, and acceptable failure modes in safety-critical contexts [27].

2.3.5. Development Directions: Engineering Aspects—AI and IoT

IoT adoption supports expanded sensing, integration with building management systems, and improved situational awareness. Engineering trajectories include sensor fusion, edge computing for local functionality under connectivity loss, interoperability, and integration of geospatial and building data [26,28]. Wildfire technology assessments highlight promise but underscore dependence on implementation choices and coordination [29].

2.3.6. Development Directions: Legislative Aspects

Regulatory evolution occurs through state/local adoption of model codes and standards; a strength is structured revision infrastructure. ICC documents a governmental consensus model and ongoing development cycle [26]. NFPA similarly documents consensus-based revision cycles [25]. Legislative attention increasingly focuses on wildfire risk and technology integration and on cyber risk governance for municipal/infrastructure IoT deployments relevant to life-safety systems [26,28].

2.4. European Union and United Kingdom

2.4.1. Legal and Normative Systems

Fire-safety governance in the EU and UK reflects long-term regulatory maturation, reinforced by EU-level harmonisation of technical standards, stronger accountability mechanisms, and progressive digitalisation of documentation and inspection workflows [45]. A key EU driver is the Construction Products Regulation (CPR), supporting a common technical language for performance assessment and comparison [31]. Fire performance is commonly expressed through standardised European classification frameworks (e.g., EN 13501 series) [32].

The revised Energy Performance of Buildings Directive (EPBD recast) has accelerated building data infrastructures and digital management, indirectly affecting compliance ecosystems by strengthening requirements around building performance information. The directive entered into force on 28 May 2024 and is to be transposed by 29 May 2026 [31,33].

National regulations remain important (e.g., Germany's model building code as reference, the Netherlands' Bbl, France's IGH/ERP frameworks) [34–36]. In the UK, post-Grenfell reforms strengthened duties, documentation, and inspection. The Fire Safety Act 2021 clarified scope (including external walls), while the Fire Safety (England) Regulations 2022 operationalised information and management obligations [37–39].

Cyber risk and data protection are cross-cutting issues as systems connect to digital platforms. GDPR and the EU Cybersecurity Act provide governance constraints and certification context relevant to smart-building safety systems [40,41].

2.4.2. Development Directions: Technological Aspects

Three clusters dominate: BIM-enabled compliance and life-cycle documentation; distributed sensing and smart-building platforms; and AI-supported risk analytics [42]. BIM increasingly functions as a backbone for coordinated design, verification, and auditable updates during operation, aligning with broader digitalisation expectations [31]. IoT deployments support continuous monitoring and predictive maintenance; AI reduces false alarms and supports early warning and scenario testing [42].

2.4.3. Development Directions: Urban-Planning Aspects

Urban fire-safety planning is increasingly linked to smart-city infrastructures, including sensor networks, geospatial platforms, and scenario-based risk modelling. Advanced use cases combine real-time data, GIS dashboards, and simulation layers for evacuation and smoke spread [42]. Post-Grenfell policy emphasised vulnerability management in high-rise housing and the need for up-to-date building information and demonstrable inspection regimes [37,38].

2.4.4. Development Directions: Organisational Aspects

A clear trend is strengthening duty-holder responsibility combined with digitalised inspection evidence and information exchange with fire and rescue services. In England, the "Responsible Person" framework is reinforced through post-Grenfell reforms and supporting guidance [37–39]. Across EU states, inspection regimes vary but show a move toward digital protocols: registries of inspection results, standardised reporting, and faster escalation of non-compliance, constrained by cybersecurity and lawful data processing [40,41].

2.4.5. Development Directions: Engineering, AI, and IoT

The technical centre of gravity shifts from isolated subsystems toward integrated, data-driven architectures supporting continuous monitoring, automated diagnostics, and context-aware response [42]. Cybersecurity and privacy become engineering requirements; secure architectures and resilient fallbacks are treated as baseline conditions [40,41].

2.5. Similarities Among Fire-Safety Regulations in Asia, the USA, Europe, and the UK

A shared cornerstone across regions is the primacy of life safety and reduction of losses due to fire. Most systems require integrated early-warning and alarm solutions as prerequisites for permitting/commissioning/operation, especially in public, commercial, and high-rise residential buildings [1,6]. Compartmentation, protected means of egress with emergency lighting and signage, and smoke-control measures are broadly convergent principles [1]. Automatic suppression is commonly required above thresholds of height/area/occupancy, reflecting a comparable scalable risk logic [1]. Maintenance, testing, and documentary traceability are emphasised in all systems [6]. Finally, risk-informed and performance-based approaches are increasingly accepted in principle to enable innovative and complex buildings, provided equivalence can be demonstrated through engineering analysis and modelling [1].

2.6. Differences Among Fire-Safety Regulations in Asia, the USA, Europe, and the UK

Europe is characterised by strong harmonisation and conformity pathways, relying on standardised performance classification and extensive EN/ISO use, fostering comparability while placing high demands on documentation and conformity workflows [1,31]. The UK operationalises a risk-based governance logic with strengthened duty-holder accountability and traceability after Grenfell [37,38].

The USA is distinctive for decentralised adoption of model codes, producing variability across jurisdictions. The approach is often granular regarding egress dimensions, sprinkler triggers, and material classifications; innovation is possible but acceptance varies locally [23,24]. Asia is heterogeneous: Japan combines rigour with structured alternative-solution pathways [2,43]. while China's multilayered system is strongly enforced but can be uneven in effectiveness depending on local capacity [1,16]. A key differentiator across regions is how alternative solutions are admitted and

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 February 2026 doi:10.20944/preprints202602.1202.v1

evaluated: mature fire-safety engineering cultures institutionalise PBD through accepted methods and review pathways; more prescriptive contexts provide fewer formal mechanisms [1,43].

2.7. Global Development Directions in Fire Safety

Five interconnected trajectories dominate: (1) international harmonisation and standardisation to support comparability of products and verification methods [31,44]; (2) digitally enabled life-cycle safety management with auditable digital records and compliance dashboards [6,7]; (3) expansion of performance-based engineering using modelling and simulation for complex buildings [1,22] (; (4) inclusive evacuation and protection of vulnerable users through clearer communication and adaptive strategies [6]; and (5) professionalisation and safety culture via routine drills, competence development, and simulation-based training [2,13].

3. Methodology

3.1. General Assumptions and Methodological Objective

The methodological design follows the objective: to compare fire-safety regulatory regimes in Japan, China, the USA, and selected EU countries plus the UK, focusing on readiness to implement BIM/DT/AI/IoT and responsive-architecture approaches, and to derive recommendations for Poland. The study is qualitative and comparative, combining targeted review of legal/regulatory documents and literature, cross-system comparison of organisational arrangements, structured content analysis with a unified template, and interpretive synthesis.

Jurisdiction selection was purposive: Japan as highly rigorous with openness to PBD and advanced digital practice [2,9]. China as rapidly modernising with strong digitalisation and increasing PBD use [16,19]; the USA as decentralised, code-based with active debate on AI/IoT and strong standards ecosystems [23,26]; and EU/UK as harmonised with expanding digital building documentation and post-Grenfell accountability [31,37].

Sources were collected in four groups: (1) legal acts and codes/standards (e.g., ICC/NFPA; EN/ISO; GB 50016; Japanese acts); (2) government and international documents [13,36]; (3) scientific and professional literature (Fire, Sensors, Applied Sciences, etc.); and (4) case studies and implementation evidence (smart-city platforms, digital twins, robotics/drones, digital registers). The temporal scope focused on 2018–2025, reflecting accelerated diffusion of digitalisation, BIM, and AI into fire-safety engineering and governance.

3.2. Analytical Framework and Content Categorization

For each jurisdiction (Japan, China, USA, EU/UK), material was coded into six categories: binding regulations; technological development; urban-planning development; organisational development; engineering developments (AI/IoT/BIM/robotics and PBD); and legislative evolution. Additional indicators tracked: presence of formal alternative-solution pathways (PBD), formal recognition of digital registers/BIM in documentation, and explicit cybersecurity requirements for connected safety ecosystems.

3.3. Comparative Synthesis and Implications for Poland

Findings were consolidated in three steps: similarities (Section 2.5), differences/gaps (Section 2.6), and development directions (Section 2.7), mapped to potential reforms for Poland. Criteria included presence of solutions in law/practice, degree of legal anchoring, implementation scale, and feasibility of transfer to Poland without undermining existing legal structures.

3.4. Methodological Limitations

The approach is qualitative and selective, covering representative models rather than all countries within each region. It relies primarily on accessible (often open-access) documents; internal operational guidance may not be captured. Nevertheless, the framework supports identification of dominant regulatory and technological patterns relevant to responsive architecture and digital fire-safety governance.

3.5. Expert Rating Procedure and Robustness

The work was assessed by P.K., who conducted the analysis and assigned the ratings based on the predefined criteria and the referenced sources. The assigned scores and the resulting tables were subsequently reviewed by W.B. and R.P., who performed an independent plausibility check for consistency and alignment with the cited evidence.

There was a verification step. After the initial ratings were assigned by P.K., the tables and assigned values were independently reviewed by W.B. and R.P. (acting as second reviewers), who checked the consistency of the scores and their alignment with the cited sources.

The values were assigned based on predefined rating criteria (scale anchors) and an evidence-based source review. Each score was derived from the content analysis of legal acts, codes/standards, and guidance documents, and then cross-checked against governmental/agency reports and documented implementation examples. In other words, the ratings reflect what could be verified in the cited documents and practice, rather than the author's intuition.

The procedure is replicable because it is based on clearly described criteria (scale anchors) and on specific, cited sources. Another researcher applying the same rating rubric and reviewing the same set of documents can reproduce the scoring logic and obtain comparable results. It should only be noted that, as an expert synthesis, the method may yield minor interpretive differences, although the assessment process itself remains replicable.

4. Results

The comparative analysis of regulations and implementation practices in Japan, China, the USA, and the EU/UK enabled identification of consistent result clusters. First, across all systems, life safety and operational continuity are dominant priorities. This translates into mandatory detection, alarm, and evacuation solutions, and increasingly explicit responsibility assigned to owners/managers to maintain fire-protection performance across the building life cycle [1,6]. Second, despite shared goals, regimes differ in centralisation, admissibility and maturity of PBD, and the pace and legal form through which BIM/DT/AI/IoT are incorporated into compliance and operations [19,24,37]. Third, a convergence of long-term development trajectories is visible: all regions transition from static prescriptive fire safety toward data-driven governance, continuous monitoring, and digital life-cycle documentation [13,42].

To represent the qualitative synthesis, an expert comparative assessment was developed across five dimensions (D1–D5), with Poland included as a reference baseline.

Table 1. Comparative maturity assessment of selected regulatory and implementation dimensions (D1–D5) across Japan, China, the USA, the EU/UK, and Poland (reference). Values reflect qualitative content analysis and represent an expert comparison.

Dimension	Japan	China	USA	EU/UK	Poland (reference)
D1—Performance-Based Design (PBD) pathway maturity	5	4	4	3	1
D2—Legal status of BIM/DT in regulations and procedures	3	4	2	4	1
D3—AI/IoT applications in fire safety (practice)	4	5	3	3	1

Dimension	Japan	China	USA	EU/UK	Poland (reference)
D4—Digital registers and life-cycle documentation	3	4	2	5	1
D5—Cybersecurity requirements for SSP/DSO/BMS/IoT	3	3	3	5	1

4.1. Key Governance Patterns: Centralisation, PBD, and Digital Readiness

Japan represents a rigorous yet operationally flexible regime supported by established pathways for alternative solutions validated through engineering analysis and simulation [2,11]. China combines strict catalogue-type requirements with a rapidly growing role of PBD, particularly in complex and high-rise facilities [16,22]. The USA relies on decentralised adoption of ICC/NFPA model codes, producing heterogeneous uptake of new editions and uneven readiness for BIM/AI integration across jurisdictions [23,24]. The EU/UK show strong harmonisation while placing explicit emphasis on accountability, traceability, and audit-ready digital documentation, especially after Grenfell [37,38].

4.2. Transferable Good Practices and Adaptation Potential in Poland

A set of good practices was extracted and assessed for adaptation potential, together with key barriers (Tables 2–6).

Table 2. Good practice: formal PBD pathway for complex buildings—characteristics, leading regions, adaptation potential in Poland, and main implementation barriers. The assessment reflects qualitative content analysis and represents expert analytical judgement.

Item	Content
Good practice	Formal PBD pathway for complex buildings
Regions where established	USA; Japan; China
Short description	Clear procedures for alternative solutions justified via engineering analyses and simulations (e.g., CFD, evacuation models, scenario-based evidence)
Adaptability to Poland	High
Main barriers	Lack of national guidance; insufficient competence; uncertainty/limited capacity of authorities to review PBD submissions

Table 3. Good practice: digital register of buildings and fire-protection systems—characteristics, leading regions, adaptation potential in Poland, and main implementation barriers. The assessment reflects qualitative content analysis and represents expert analytical judgement.

Item	Content
Good practice	Digital register of buildings and fire-protection systems
Regions where established	EU/UK; selected Japanese smart-city programmes

 doi:10.20944/preprints202602.1202.v1

Item	Content
Short description	Central repository of building data, safety systems, inspections, and compliance evidence across the life cycle
Adaptability to Poland	High
Main barriers	Implementation costs; lack of standardised data format and governance model

Table 4. Good practice: "Golden Thread" life-cycle documentation (UK example)—characteristics, adaptation potential in Poland, and main implementation barriers. The assessment reflects qualitative content analysis and represents expert analytical judgement.

Item	Content
Good practice	"Golden Thread" life-cycle safety documentation
Regions where established	United Kingdom
Short description	Continuous, updated technical and fire-safety documentation maintained across the building life cycle to ensure traceability and accountability
Adaptability to Poland	High
Main barriers	Legal responsibility models; increased duties for building managers; enforcement capacity

Table 5. Good practice: BIM requirements in approvals and commissioning—characteristics, leading EU examples, adaptation potential in Poland, and main implementation barriers. The assessment reflects qualitative content analysis and represents expert analytical judgement.

Item	Content
Good practice	BIM requirements in approvals and commissioning procedures
Regions where established	Selected EU countries (implementation varies)
Short description	BIM used as standard information format for design coordination, inspection-relevant attributes, and change/as-built management linked to approvals
Adaptability to Poland	High
Main barriers	Costs; uneven market readiness; limited awareness and institutional readiness in approval authorities; IT/OT coordination

Table 6. Good practice: minimum cybersecurity requirements for SSP/DSO/BMS/IoT systems—characteristics, leading regions, adaptation potential in Poland, and main implementation barriers. The assessment reflects qualitative content analysis and represents expert analytical judgement.

 doi:10.20944/preprints202602.1202.v1

Item	Content
Good practice	Minimum cybersecurity requirements for integrated safety systems (SSP/DSO/BMS/IoT)
Regions where established	EU (cybersecurity governance frameworks); selected US contexts (critical infrastructure guidance)
Short description	Network segmentation, update obligations, access control, logging, and resilience testing for safety-critical building systems
Adaptability to Poland	Medium
Main barriers	IT/OT coordination; costs; limited expertise; weak cybersecurity culture in building operations

4.3. Regional Readiness for Responsive Architecture and Digital Fire Safety

Japan and leading Chinese cities appear as leaders in city-scale approaches where building-level safety integrates with municipal data platforms, risk mapping, and crisis-management coordination—making dynamic evacuation steering a plausible "next step" rather than an exception [13,19]. In the USA, advanced detection and modelling are prominent in wildfire contexts, but BIM–IoT–AI integration in conventional building fire safety remains uneven and jurisdiction-dependent [23,36]. In the EU/UK, the regulatory emphasis is often on traceable digital documentation, registers, and enforceable accountability, creating procedural foundations for digital twins and more dynamic safety management [37,42].

4.4. Trend Readiness Mapping (Ten Global Trends)

Ten trends were assessed using a 0–10 scale and interpretive labels: A—trend essentially absent; B—present mainly in strategies/literature; C—clearly present in regulations and/or practice.

4.5. Implications for Poland: Transferable Practices Versus Structural Gaps

The results provide a structured map of transferable practices and regulatory gaps relevant to Poland. Transferable building blocks include: (i) clearly defined PBD pathways supported by simulation evidence; (ii) enforceable digital documentation and registers (BIM/as-built/fire-safety registers); (iii) stronger coupling of building-scale fire safety with metropolitan risk governance; and (iv) baseline cybersecurity controls for SSP/DSO/BMS/IoT systems (see Tables 1–7). Key gaps include lack of coherent national digital registers, absence of formal frameworks for responsive/dynamic evacuation, limited data quality governance, and weak formal acknowledgement of cyber resilience in safety compliance. Overall, global fire-safety regulation is moving toward a new "regulatory language" that includes control logic, interoperability, cyber resilience, and formal roles for BIM/DT as official compliance evidence—areas where Poland currently lags most visibly.

Table 7. Comparative readiness assessment (0–10) for ten global trends in fire-safety governance across Japan, China, the USA, the EU/UK, and Poland (reference). Values reflect qualitative content analysis and represent an expert comparison rather than a statistical measurement. Scale label interpretation: A—trend largely absent; B—present mainly in strategies/literature; C—clearly present in regulations and/or implementation practice.

Trend	Japan	China	USA	EU/UK	Poland
1. Formal PBD pathways for complex buildings	9 (C)	8 (C)	8 (C)	6 (B/C)	1 (A)

Trend	Japan	China	USA	EU/UK	Poland
2. BIM linked to approvals and commissioning	6 (B)	8 (C)	5 (B)	8 (C)	1 (A)
3. Digital registers of buildings and fire systems	6 (B)	7 (C)	4 (B)	8 (C)	1 (A)
4. Data quality and update requirements	6 (B)	7 (C)	4 (B)	7 (C)	1 (A)
5. Regulatory references to AI/IoT	7 (C)	8 (C)	5 (B)	5 (B)	1 (A)
6. Integration with smart-city fire governance	7 (C)	9 (C)	5 (B)	5 (B)	1 (A)
7. Minimum cybersecurity requirements	6 (B/C)	5 (B)	5 (B)	8 (C)	1 (A)
8. Formal responsibility allocation (e.g., Responsible Person; AHJ)	6 (B)	5 (B)	8 (C)	8 (C)	2 (A/B)
9. Digital documentation linked to audits/inspections	7 (C)	7 (C)	5 (B)	8 (C)	1 (A)
10. Explicit inclusion of responsive/dynamic systems	7 (C)	8 (C)	5 (B)	5 (B)	1 (A)

5. Discussion

The comparative review confirms a clear convergence of long-term trajectories: fire safety is moving beyond static prescriptive logic toward data-driven governance, scenario-based engineering verification, and incorporation of digital technologies enabling continuous monitoring and adaptive response [1,42]. However, the pace and pathways differ due to regulatory culture, enforcement models, and institutional capacity.

5.1. Sustainability and Lifecycle Governance Implications

The comparison indicates that the most sustainability-relevant regulatory advances are those that reduce systemic risk over the building lifecycle: (i) formal pathways for performance-based design (PBD) that enable verifiable equivalence under novel configurations, (ii) auditable digital documentation that remains current during operation, and (iii) governance of cyber-physical dependencies in integrated safety systems [24,25,28,37]. These elements support resilient building operation and reduce the probability that latent defects accumulate unnoticed until an incident occurs.

The EU/UK trajectory illustrates how accountability and "information continuity" can become core safety mechanisms, with digital documentation functioning as a resilience infrastructure that supports inspections, maintenance, refurbishment decisions, and emergency response access to reliable data [31,37,38]. Japan and leading metropolitan contexts in China demonstrate a complementary sustainability pathway: city-scale data platforms and smart-risk mapping that connect building safety to district-level preparedness and crisis governance [13]. In the US context, decentralised innovation can accelerate technological experimentation, but sustainability outcomes depend on consistent adoption and governance capacity across jurisdictions, particularly where wildfire exposure and evacuation constraints are intensifying [26,29].

For Poland, the sustainability implication is that closing the "digital governance gap" is not solely a technological upgrade but a resilience strategy: predictable PBD procedures, minimum requirements for digital fire-safety asset information, and baseline cyber resilience controls would increase reliability of protection measures over decades of operation and across refurbishment cycles, while also improving inclusiveness for vulnerable users through better verified evacuation strategies [1,6].

Japan combines high rigour with operational flexibility due to mature acceptance of PBD supported by simulation-based justification, enabling innovation without undermining accountability [2,21]. A similar direction is visible in the EU and UK, shaped strongly by post-incident reforms—especially after Grenfell—where the shift reinforced documentation governance, responsibility allocation, and inspection traceability [37,38]. Approaches such as "Golden Thread" indicate a move toward life-cycle safety information management as a regulatory expectation rather than a best-effort practice (see Tables 3–4).

China and the USA show strong innovation capacity but more heterogeneous regulatory environments. In China, national standards remain central while smart-city platforms, digital twins, and AI-enabled supervision accelerate in major urban centres [16,19]. The USA's decentralised adoption of model codes creates a dynamic environment but uneven maturity across jurisdictions [23,24]. As a result, AI/IoT solutions may be advanced in certain municipalities and projects but remain marginal elsewhere.

From the responsive-architecture perspective—real-time coupling between systems, occupants, and operational data—Japan, leading Chinese cities, and several EU/UK pathways provide the most coherent conditions for dynamic functionality (adaptive signalling, variable smoke-control logic, stronger integration with emergency governance) because they combine technology adoption with formal verification pathways and documentation governance (see Tables 2–6). Digitalisation also introduces a systemic vulnerability: cybersecurity and data trust. As SSP/DSO, BMS, IoT networks, and AI analytics integrate, failures or attacks may propagate across the safety ecosystem. European governance increasingly treats cybersecurity controls (segmentation, logging, update policies) as safety-relevant requirements aligned with broader cybersecurity frameworks [28,41], whereas Poland remains largely focused on static requirements with limited formal treatment of cyber resilience as a fire-safety concern (see Table 6).

Overall, the key limitation for Poland is not technological feasibility but the absence of repeatable legal pathways and verification routines that would make responsive solutions scalable and institutionally accepted. Without such pathways, advanced solutions remain project-specific and negotiation-dependent.

6. Recommendations

6.1. Establish a Clear National Pathway for Performance-Based Design (PBD)

Poland should establish an alternative compliance route for complex buildings through PBD. This should complement, not replace, prescriptive requirements. National guidance should define eligible typologies, accepted methods (CFD, evacuation simulation, RSET/ASET reasoning), scenario requirements, documentation standards, and review expectations for submissions evaluated by authorities (see Table 2) [1,22].

6.2. Formalise BIM and Digital Twins (DT) as Compliance and Operational Evidence

Poland should establish an alternative compliance route for complex buildings through PBD. This should complement, not replace, prescriptive requirements. National guidance should define eligible typologies, accepted methods (CFD, evacuation simulation, RSET/ASET reasoning), scenario requirements, documentation standards, and review expectations for submissions evaluated by authorities (see Table 2) [1,22].

6.3. Introduce a Regulatory Definition and Verification Logic for Responsive Fire-Safety Systems

Poland should acknowledge responsive architecture as fire-safety relevant and define functional expectations (response times, fail-safe principles, manual override, testing protocols) rather than enumerating technologies. Pilot programmes under enhanced supervision could support controlled learning and reduce adversarial interpretation conflicts.

6.4. Implement Minimum Cybersecurity Requirements for Integrated Safety Systems

Baseline controls for high-importance buildings should include segmentation, update policies, logging, controlled access, and periodic resilience testing. These can begin as a minimum catalogue aligned with evolving EU practice and critical infrastructure principles (see Table 6) [28,41].

6.5. Build Human Capacity and Interdisciplinary Competence

Training should bridge classical fire engineering with BIM/DT, data literacy, AI-supported decision tools, and IT/OT risk awareness. Practical guidance documents with examples can support implementation.

6.6. Strengthen Coordination Across Regulatory and Institutional Domains

Because these issues span building law, fire regulation, digitalisation, emergency management, and data protection, Poland should establish (or strengthen) an inter-institutional coordination mechanism focused on the fire safety–data–digital technologies nexus to ensure coherent reforms and prioritised pilots.

6.7. Policy and Practice Roadmap

To operationalise the recommendations, a staged roadmap is advisable. In the short term, Poland could (i) issue national PBD guidance for defined complex-building categories, (ii) define a minimum digital fire-safety information set linked to BIM deliverables for approvals and as-built updates, and (iii) introduce a minimum cyber hygiene catalogue for safety-critical building systems in high-importance facilities [28,31]. In the medium term, a national or sectoral digital register model can be piloted for hospitals, transport hubs, and large public buildings, aligned with interoperable data standards and inspection protocols [31,38]. In the long term, responsive fire safety can be formalised through performance-oriented verification routines and lifecycle accountability mechanisms, ensuring that dynamic systems remain testable, auditable, and resilient under both technical failure and cyber stress [40,41].

7. Conclusions

This paper compared the fire-safety regulatory frameworks and implementation practices of Japan, China, the USA, and selected EU/UK systems, focusing on readiness to accommodate BIM, DT, AI, and IoT as enablers of responsive fire-safety architecture. Despite divergent legal traditions, the analysis indicates convergence toward a common strategic goal: moving beyond static compliance toward data-driven, scenario-based, and life-cycle-oriented fire safety.

Japan shows one of the most mature environments for PBD supported by structured alternative-solution pathways [2]. China demonstrates rapid modernisation and strong integration of AI/IoT and city-scale platforms in major metropolitan contexts [16,19]. The USA remains highly innovative but decentralised, with uneven adoption across jurisdictions [23]. The EU/UK pathway is shaped by harmonisation and governance reforms, with an advanced focus on digital documentation, traceability, and accountability after major incidents such as Grenfell [31,38].

Across regions, fire safety is increasingly treated as an operational and informational infrastructure integrating design, inspection, maintenance, and emergency response. This enables a shift from static to adaptive fire safety where dynamic evacuation guidance, sensor-based risk monitoring, and continuous compliance evidence become realistic components of the safety ecosystem [7]. For Poland, the national environment remains comparatively mature in prescriptive requirements but underprepared for systematic implementation of digital and responsive approaches—particularly PBD pathways, BIM/DT as compliance evidence, digital registers, and cybersecurity requirements for integrated SSP/DSO/BMS/IoT systems. Closing this gap requires regulatory clarification, institutional capacity building, and interoperable data governance.

This study contributes a structured cross-regime comparison focused on regulatory readiness for data-driven, responsive fire safety—highlighting that the decisive factor is not technology

 doi:10.20944/preprints202602.1202.v1

availability but the existence of repeatable legal pathways, verification routines, and lifecycle information governance. From a sustainability perspective, these mechanisms function as resilience infrastructure for the built environment by reducing lifecycle risk, supporting inclusive evacuation, and enabling auditable safety performance in digitally integrated buildings and cities [13,28,37]

Author Contributions: Conceptualization, [W.B; P.K.]; methodology, [P.K.]; formal analysis, [P.K]; investigation, [P.K]; resources, [P.K]; writing—original draft preparation, [P.K.]; writing—review and editing, [W.B; R.P]; visualization, [P.K.]; supervision, [W.B; R.P]. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The author(s) would like to thank the institutions and researchers whose open-access publications and reports supported this comparative study.

Conflicts of Interest: The author(s) declare no conflict of interest.

Abbreviations

AI	Artificial Intelligence;
AHJ	Authority Having Jurisdiction;
ASET	Available Safe Egress Time;
BIM	Building Information Modelling;
BMS	Building Management System;
BEMS	Building Energy Management System;
CFD	Computational Fluid Dynamics;
CPR	Construction Products Regulation;
DT	Digital Twin;
DSO	Voice Alarm System;
EN	European Standard;
EPBD	Energy Performance of Buildings Directive;
EU	European Union;
GAO	U.S. Government Accountability Office;
ICC	International Code Council;
IFC	International Fire Code;
IBC	International Building Code;
IoT	Internet of Things;

References

1. Östman, B.; Barber, D.; Dagenais, C.; et al. Fire Safety Requirements in Different Regions. In Fire Safe Use of Wood in Buildings: Global Design Guide; CRC Press: Boca Raton, FL, USA, 2022; pp. 117–148. Available online: (accessed on 22 January 2026).
2. Sekizawa, A. Study on Potential Alternative Approach for Fire Deaths Reduction. Fire Safety Science 2000, 6, 171–181. Available online: (accessed on 22 January 2026).
3. Rowan, L.R. (Coordinator). Building Codes, Standards, and Regulations: Frequently Asked Questions; Congressional Research Service Report R47665; CRS: Washington, DC, USA, 2025. Available online: (accessed on 22 January 2026).
4. Home Office. Fire Safety Act 2021: Fact Sheet. 2021. Available online: (accessed on 22 January 2026).
5. UK Government. The Fire Safety (England) Regulations 2022 (S.I. 2022/547). 2022. Available online: (accessed on 22 January 2026).

6. Jones, N.; Petrov, I.; Jane, K. Regulatory Compliance and Standards: Comparison of International Fire Safety Standards. Civil Engineer and Researcher, Tunneling and Trenchless Technology; Taipei, Taiwan, September 2024. Available online: (accessed on 22 January 2026).
7. Negi, P.; et al. Integration of Industry 4.0 Technologies in Fire and Safety Management. Fire 2024, 7, 335. Available online: (accessed on 22 January 2026).
8. Home Office. Fire Safety (England) Regulations 2022: Fire Door Guidance. 2023. Available online: (accessed on 22 January 2026).
9. Khan, F.; Xu, Z.; Sun, J.; Khan, F.M.; Ahmed, A.; Zhao, Y. Recent Advances in Sensors for Fire Detection. Sensors 2022, 22, 3310. Available online: (accessed on 22 January 2026).
10. Zhang, Y.; Wang, G.; Wang, X.; Kong, X.; Jia, H.; Zhao, J. Regional High-Rise Building Fire Risk Assessment Based on the Spatial Markov Chain Model and an Indicator System. Fire 2024, 7, 16. Available online: (accessed on 22 January 2026).
11. Bi, H.; Gelenbe, E. A Survey of Algorithms and Systems for Evacuating People in Confined Spaces. Electronics 2019, 8, 711. Available online: (accessed on 22 January 2026).
12. Yang, Y.; Du, H.; Yao, G. A Scientometric Research on Applications and Advances of Fire Safety Evacuation in Buildings. Fire 2023, 6, 83. Available online: (accessed on 22 January 2026).
13. UN ESCAP. Independent Comprehensive Review of the Establishment of the Asian and Pacific Centre for the Development of Disaster Information Management (APDIM); United Nations Economic and Social Commission for Asia and the Pacific: Bangkok, Thailand, 2025. Available online: (accessed on 22 January 2026).
14. Zhang, S.; Zhu, Z.; Zhang, H.; Zhang, H. Research on the Evacuation of People from a Road Tunnel Fire Based on a Mathematical Model. Heliyon 2024, 10, e23016. Available online: (accessed on 22 January 2026).
15. UN ESCAP. Asia-Pacific Report on Population and Development; United Nations Economic and Social Commission for Asia and the Pacific: Bangkok, Thailand, 2023. Available online: (accessed on 22 January 2026).
16. Fire Protection Law of the People's Republic of China (Amended in 2021) (English translation). 2021. Available online: (accessed on 22 January 2026).
17. Standardization Administration of China. GB 50016-2014 (2018 Edition): Code for Fire Protection Design of Buildings. 2018. Available online: (accessed on 22 January 2026).
18. Xu, W.; Chan, S.C.; Leong, W.Y. Effectiveness Study of Artificial Intelligent Facility System in Maintaining Building Fire Safety (Case Study: Typical Public Building Cases of Fire-Fighting Facilities Management in China). Discrete Dynamics in Nature and Society 2023, 2592322. Available online: (accessed on 22 January 2026).
19. Su, L.-C.; Wu, X.; Zhang, X.; Huang, X. Smart Performance-Based Design for Building Fire Safety: Prediction of Smoke Motion via AI. Journal of Building Engineering 2021, 43, 102529. Available online: (accessed on 22 January 2026).
20. Zhang, C. Review of Structural Fire Hazards, Challenges, and Prevention Strategies. Fire 2023, 6, 137. Available online: (accessed on 22 January 2026).
21. Bai, M.; Liu, Q. Evaluating Urban Fire Risk Based on Entropy-Cloud Model Method Considering Urban Safety Resilience. Fire 2023, 6, 62. Available online: (accessed on 22 January 2026).
22. Jia, X.; Wang, Y.; Chen, J.; Fang, Z.; Xia, K.; Wang, H. Performance-Based Fire-Protection Design of Public Amenities with Restrained Personnel Activities. Fire 2023, 6, 256. Available online: (accessed on 22 January 2026).
23. Rowan, L.R. (Coordinator). Building Codes, Standards, and Regulations: Frequently Asked Questions; Congressional Research Service Report R47665; CRS: Washington, DC, USA, 2025. Available online: (accessed on 22 January 2026).
24. ICC (International Code Council). Code Development Process. 2024. Available online: (accessed on 22 January 2026).
25. NFPA (National Fire Protection Association). Standards Development Process. 2025. Available online: (accessed on 22 January 2026).

26. GAO (U.S. Government Accountability Office). Science & Tech Spotlight: Wildfire Detection Technologies; GAO-25-108161; GAO: Washington, DC, USA, 2025a. Available online: (accessed on 22 January 2026).
27. Chandler, S. The Potential for Artificial Intelligence and Machine Learning; U.S. Fire Administration (USFA)/FEMA: Emmitsburg, MD, USA, 2024. Available online: (accessed on 22 January 2026).
28. NIST (National Institute of Standards and Technology). Internet of Things (IoT) Advisory Board (IoTAB) Report; NIST: Gaithersburg, MD, USA, 2024. Available online: (accessed on 22 January 2026).
29. GAO (U.S. Government Accountability Office). Wildfire Management: Technologies for Forecasting, Detection, Mitigation, and Response; GAO-25-108589; GAO: Washington, DC, USA, 2025b. Available online: (accessed on 22 January 2026).
30. Ingram Micro; US Ignite. Primer IoT: Putting the "Smart" into Smart Cities; US Ignite: Washington, DC, USA, 2020. Available online: (accessed on 22 January 2026).
31. European Commission. Construction Products Regulation (CPR). 2024. Available online: (accessed on 22 January 2026).
32. RISE (Research Institutes of Sweden). European Fire Classification of Construction Products—EN 13501. 2026. Available online: (accessed on 22 January 2026).
33. EUR-Lex. Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the Energy Performance of Buildings (Recast). Official Journal of the European Union, 2024. Available online: (accessed on 22 January 2026).
34. Business.gov.nl. Rules for Construction in the Netherlands (Besluit bouwwerken leefomgeving, Bbl). 2026. Available online: (accessed on 22 January 2026).
35. Legifrance. Règlement de sécurité pour la construction des immeubles de grande hauteur (IGH)—Selected provisions. 2025. Available online: (accessed on 22 January 2026).
36. Préfecture de Police (France). Sécurité incendie des ERP dont hébergement et des IGH. 2024. Available online: (accessed on 22 January 2026).
37. Home Office. Fire Safety Act 2021: Fact Sheet. 2021. Available online: (accessed on 22 January 2026).
38. UK Government. The Fire Safety (England) Regulations 2022 (S.I. 2022/547). 2022. Available online: (accessed on 22 January 2026).
39. Home Office. Fire Safety (England) Regulations 2022: Fire Door Guidance. 2023. Available online: (accessed on 22 January 2026).
40. EUR-Lex. Regulation (EU) 2016/679 (General Data Protection Regulation)—Summary. 2016. Available online: (accessed on 22 January 2026).
41. EUR-Lex. Regulation (EU) 2019/881 (EU Cybersecurity Act)—Summary. 2019. Available online: (accessed on 22 January 2026).
42. Negi, P.; et al. Integration of Industry 4.0 Technologies in Fire and Safety Management. Fire 2024, 7, 335. Available online: (accessed on 22 January 2026).
43. Nakahara, Y. Comparison of Fire Protection Laws between Japan and East Asian Countries 2024. Available online: (accessed on 22 January 2026).
44. RISE (Research Institutes of Sweden). European Fire Classification of Construction Products—EN 13501. 2026. Available online: (accessed on 22 January 2026).
45. Sheridan, L.; Visscher, H.J.; Meijer, F.M. Building Regulations in Europe. Part II: A Comparison of Technical Requirements in Eight European Countries. Delft University of Technology, 2003. Available online: (accessed on 22 January 2026).
46. Alazbah, A.A.; Rabie, O.; Al-Barakati, A. Crowd Evacuation in Stadiums Using Fire Alarm Prediction. Sensors 2025, 25, 2810. Available online: (accessed on 22 January 2026).
47. He, L.; Zhou, Y.; Liu, L.; Zhang, Y.; Ma, J. Research and Application of Deep Learning Object Detection Methods for Forest Fire Smoke Recognition. Scientific Reports 2025, 15, 16328. Available online: (accessed on 22 January 2026).

 doi:10.20944/preprints202602.1202.v1

disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.