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Posted Date: 6 February 2026

doi: 10.20944/preprints202602.0570.v1

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Responsive Architecture in Practice: BIM/DT/AI/IoT for Dynamic Evacuation—Case Studies

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Abstract

Dynamic fire-safety systems are no longer futuristic; they are a viable alternative to rigid, prescriptive approaches to occupant protection and evacuation. This paper analyses three case studies where Building Information Modelling (BIM), a Digital Twin (DT), Internet-of-Things (IoT) sensor networks, Artificial Intelligence (AI) control algorithms, and dynamic evacuation signage were integrated to support a Dynamic Fire-Safety System (DFS). Secondary research covered a university building in Lille, the Beijing Capital Airport Emergency Center, and a shopping mall in the Taipei 101 high-rise complex. All facilities meet formal requirements, yet a BIM/DT/IoT/AI layer suggests better performance under fire conditions. Methods included a structured literature review, BIM-based fire modelling in Fire Dynamics Simulator (FDS), evacuation simulations, and comparison of static versus dynamic paradigms. The workflow reconstructs fire–evacuation scenarios to assess time-dependent tenability, exit viability, and congestion-driven bottlenecks. In Lille, DFS serves as a computational laboratory for design decisions; in Beijing, as a decision-support core controlling signage in near real time; and in Taipei 101, as an optimisation-driven strategy for multi-storey occupant populations. Across the cases, DFS-oriented solutions are reported to shorten evacuation time and/or increase the probability of successful evacuation relative to static arrangements. Reported benefits depend on clear cue visibility and timely actuation of guidance signals. Implications for Poland are discussed: prescriptive rules should remain a baseline, while complex facilities may adopt performance-based solutions grounded in BIM/DT/IoT/AI, provided equivalence to conventional protection is demonstrated.

Keywords: BIM; digital twin (DT); IoT; artificial intelligence (AI); Dynamic Fire-Safety System (DFS); evacuation; fire modelling; Fire Dynamics Simulator (FDS); performance-based design (PBD)

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1. Introduction

1.1. Digital Transformation of Fire Safety

In recent years, fire safety has ceased to rely solely on basic installations and paper-based binders of safety instructions. Contemporary buildings—particularly hospitals, university campuses, airports, and large office complexes—operate as complex technical systems. Fire Detection and Alarm Systems (FDAS) and Voice Alarm Systems (VAS) (corresponding to the Polish systems SSP and DSO, respectively), together with a Building Management System (BMS), operate concurrently with smoke-control and ventilation systems, emergency power supply, access control, CCTV monitoring, and other subsystems. Each typically follows its own internal logic, maintains separate documentation, and is serviced under dedicated procedures. During an emergency, however, these subsystems are expected to function as an integrated whole. In practice, such integration is not always achieved.

doi:10.20944/preprints202602.0570.v1

For decades, fire-safety practice was dominated by static scenarios—developed once, approved, and archived within project documentation. Fire safety instructions would be included in facility documentation, the fire scenario embedded within the FDAS/VAS design, and evacuation procedures formalised in occupational health and safety regulations. At the time of commissioning, compliance was typically confirmed (at least formally). Over time, however, operational changes often accumulate: changes in room function, added partitions, modified interior layouts, new tenants, or additional IT systems. As a result, scenarios and procedures may become outdated, increasingly diverging from the building's actual configuration and its behaviour under fire conditions.

In parallel, design tools have evolved substantially. Three-dimensional Building Information Modelling (BIM) has become standard practice in many countries—initially as an advanced method of producing coordinated drawings, and later as a structured digital database of the facility. Advanced simulations have also become increasingly accessible and routinely applied, including Computational Fluid Dynamics (CFD)-based fire and smoke analysis, agent-based evacuation modelling (e.g., buildingExodus, Pathfinder), and tools for assessing visibility, temperature, and fire-load conditions. In contemporary workflows, digital fire and evacuation analysis is widely recognised as standard. It is possible to simulate fire development, calculate evacuation performance using the ASET/RSET framework (Available Safe Egress Time/Required Safe Egress Time), and compare multiple spatial and operational design variants. A key limitation, however, is that many such analyses effectively end at the completion of the design stage. After handover, BIM models are often not maintained as living datasets, and simulation outputs are rarely leveraged during building operation.

A further layer is provided by the Internet of Things (IoT) and continuous acquisition of operational data. Buildings increasingly incorporate dense sensor networks, including temperature, smoke, CO, airflow, occupancy-counting systems, and camera-based analytics. Consequently, BMS and FDAS platforms are no longer limited to basic alarm signalling; they increasingly function as sources of real-time or near-real-time data streams describing the facility's state. This creates a natural impetus to connect two previously separated domains: the digital model developed at the design stage and the operational data collected during use. This need has contributed to the emergence of the Digital Twin (DT) concept—a model that not only represents building geometry and key parameters but is continuously updated through sensor and operational inputs to reflect the current condition of the facility.

The subsequent step involves the application of Artificial Intelligence (AI) and Machine Learning (ML), not only in research settings but increasingly at the interface of safety-critical building systems. On the one hand, computer vision algorithms can detect smoke, flames, crowd density, or blocked exits from camera feeds; on the other, predictive models can estimate fire development or occupant movement patterns based on sensor data. These capabilities are complemented by evacuation route optimisation and real-time control functions for building components, including dynamic signage direction, operation of fire doors and smoke dampers, fire-fighter lift modes, and smoke-exhaust ventilation performance. Within this framing, a building is no longer a collection of independent installations triggered by predefined scenarios; it increasingly resembles a cyber–physical system in which decisions can be made dynamically in response to real-time data inputs.

This development can be described as the digital transformation of fire safety. It is not simply a matter of adding more detectors or introducing a single control module into an existing FDAS. Instead, it reflects a shift in the underlying logic of fire-safety thinking—from a one-time designed, static protection layout towards a system capable of responding continuously to changes over time, both during building operation (e.g., changes in use or evolving fire loads) and during the incident itself. This is also a defining characteristic of responsive architecture. Within this approach, BIM, IoT, AI, and DT are not treated as isolated technologies; they form an integrated ecosystem in which data, models, and devices cooperate to maintain occupant safety.

At the same time, this transformation cannot be considered independently of practice and regulation. On the one hand, advanced implementations are increasingly observed, including IoT-enabled dynamic evacuation systems, digital twins used for drills and emergency response planning, and AI-driven analytics supporting fire brigade operations. On the other hand, prevailing regulations, standards, and commissioning practices remain strongly rooted in static scenarios and predefined solutions. This tension—between what is technically feasible and what current regulatory frameworks permit—constitutes a key context for the development and broader adoption of DFS-oriented systems. It is within this context that the case studies presented in the remainder of the paper should be interpreted.

1.2. Aim of the Paper

The aim of this paper is to demonstrate, through concrete examples, that Dynamic Fire-Safety Systems (DFSs) based on BIM models, digital twins, IoT networks, and AI algorithms are no longer speculative concepts, but solutions that can already operate in existing buildings and built complexes. The analysed systems function under routine operational conditions, support real user populations, and are integrated with everyday fire-safety procedures. In this sense, the paper does not introduce an abstract theoretical proposal; rather, it organises and interprets selected implementations within a coherent analytical framework grounded in the DFS concept.

This framework enables seemingly heterogeneous implementations—such as a local evacuation support system deployed in a university building, an AI-assisted solution leveraging neural networks to track fire development in near real time within a medical facility, or a digital twin representing a retail centre—to be interpreted as distinct yet related responses to a common challenge: establishing a continuous operational chain from sensing and data acquisition, through computational modelling and analytics, to decision-making and actionable interventions.

The central objective is therefore to describe and compare how such systems establish a “sensor-to-decision” pathway supporting fire safety and evacuation. The analysis addresses: (i) how data are acquired and integrated from sensors, alarm systems, building automation, and IoT networks; (ii) how these data are linked to the facility’s geometric representation stored in BIM and structured within a DT environment; (iii) which computational models are applied, including CFD-based fire simulations (e.g., via FDS—Fire Dynamics Simulator), agent-based evacuation models, and ML-driven methods; and (iv) how outputs are communicated to key stakeholders, including system operators, emergency services (where applicable), and occupants, as well as whether the solutions operate in near real time or primarily support pre-event planning and scenario development.

The paper adopts a comparative case-study approach based on the literature and available source materials. The analysis draws on published implementation descriptions, system architecture diagrams, simulation results, and performance parameters reported by the original authors. The authors of this paper did not conduct primary fire experiments or evacuation drills in the analysed facilities. Nevertheless, applying a unified interpretive framework (DFS) enables the collected material to be synthesised and compared in a structured manner. The conclusions are intended to be practice-oriented, identifying which DFS components appear mature and transferable to other facilities of comparable function, and which barriers—technological, organisational, or regulatory—may constrain implementation and should be addressed in future developments.

1.3. Research Scope

The research scope is not limited to a single building typology. Three deliberately distinct examples were selected in order to examine how BIM, digital twins, IoT, and AI solutions function under different operational conditions. The first facility is a research and academic building in Lille—a typical university environment with laboratories and office-support spaces, where fire-safety systems must accommodate daily movement patterns of staff, researchers, and students.

The second case is the Beijing Capital Airport Emergency Center, a facility providing medical and emergency response functions associated with airport crisis management. Here, the emphasis shifts toward continuous operational readiness, rapid decision-making, and performance under elevated stress conditions.

The third analysed facility is a multi-storey shopping mall located within the Taipei 101 high-rise complex, which also accommodates hotel, service, office, and residential functions.

This scope can be related to the Polish fire-safety occupancy classification. The research and academic building in Lille, given its educational and laboratory functions, broadly corresponds to facilities classified in Poland as ZL I (public buildings of an educational character). The Beijing Capital Airport Emergency Center, as a medical and rescue facility, can be treated as broadly analogous to ZL II, typical of hospitals and buildings intended for persons with limited mobility. The multi-storey shopping mall forms a more complex arrangement, combining functions comparable to ZL I and ZL III (given the presence of numerous offices). Importantly, all three facilities represent high-complexity and high-responsibility building groups in terms of life safety.

Educational and laboratory facilities exhibit high diversity of users, variable familiarity with building layouts, and frequent technical-equipment constraints—factors that complicate evacuation dynamics. In the medical-rescue centre context, these challenges are intensified by the continuous presence of individuals with limited mobility and the requirement to maintain operational continuity of critical functions even during emergencies. Finally, the Taipei 101 complex combines multiple challenges and introduces further coordination demands across interconnected evacuation areas and large occupant populations. Consequently, all three cases can be considered representative of facility groups in which designing and maintaining fire-safety systems requires particularly advanced analytical and organisational capabilities.

1.4. Research Questions

In line with the aim and scope of the study, the following research questions were formulated: How does the sensor-to-decision chain operate in practice in the three analysed facilities—(a) the research building in Lille, (b) the Beijing Capital Airport Emergency Center, and (c) the shopping mall in Taipei 101—from acquiring signals from sensors and technical systems, through data processing and computational modelling, to decisions related to fire safety and evacuation?

Which key technological components are necessary to implement a Dynamic Fire-Safety System (DFS) in practice, particularly in terms of integrating BIM, digital twins (DT), IoT networks, AI algorithms, and control systems (FDAS, VAS, BMS, intelligent evacuation signage)?

To what extent can the DFS solutions presented in the case studies (Lille, Beijing, Taipei 101) be transferred to the Polish legal and regulatory context, and what changes or supplements to Polish fire-safety regulations (Technical Conditions, Ministry of the Interior and Administration regulations, State Fire Service guidelines) would be necessary to enable broader application as performance-based approaches?

1.5. Structure of the Paper

The structure of the paper follows the sequence of research steps. After the introduction and presentation of the aim, scope, and research questions, the paper outlines the DFS concept and provides a literature overview on the use of BIM, digital twins, IoT, and AI tools in fire safety. The next section describes the research methodology, including the selection of the three case studies and the principles for their comparison within a single analytical framework.

The subsequent section presents the three case studies. For each facility, the functional context, system architecture, data flows, and fire-safety- and evacuation-related functions are described. The results are then synthesised through a comparison of the maturity and development of individual DFS elements, system temporal modes of operation, and applicability to facilities corresponding to Polish categories ZL I, ZL II, and ZL III. These findings are subsequently discussed, including strengths and weaknesses of the analysed solutions, identified gaps, and implications for design and facility operation.

The paper concludes with a summary and recommendations relevant to Polish fire-safety regulations. Key conclusions regarding the functioning of DFS-oriented solutions in high-responsibility buildings are synthesised, and directions for future research and implementation

doi:10.20944/preprints202602.0570.v1

pathways are proposed to support similar solutions in Polish conditions, both at the design stage and in subsequent facility management.

2. Literature Review—Dynamic Fire-Safety System (DFS)

2.1. Concept of a Dynamic Fire-Safety System

The Dynamic Fire-Safety System (DFS) adopted in this paper emerges from the field of Fire Safety Engineering (FSE), while shifting the emphasis from individual technical installations towards a comprehensive approach focused on managing information about the facility's state. The key issue is no longer limited to the performance of a single device—for example, smoke dampers or sprinklers—but rather how information from multiple sources is collected, processed, and used in near real time when decisions must be made regarding alarms, evacuation, or crowd-management strategies. A DFS therefore assumes that the building is continuously "observable" and "controllable", rather than only during periodic inspections or design-stage analyses.

Within this framework, BIM models, digital twins, IoT sensor networks, and AI algorithms should not be regarded as optional add-ons; instead, they constitute core elements of fire-safety infrastructure. BIM provides the geometric and baseline informational structure of the facility, specifying the location of components and the original design intent. The digital twin extends this representation by incorporating real-time and near-real-time operational information derived from building automation and sensors distributed throughout the building or across the wider facility. IoT technologies enable dense, distributed data acquisition that would otherwise remain fragmented. AI algorithms, in turn, allow the system to move beyond fixed alarm thresholds by identifying patterns associated with emerging hazards, evacuation bottlenecks, or incipient component failures.

A DFS can thus be described as a sequence of interconnected steps. First, there is a sensory layer in which detectors and installed systems provide signals describing environmental conditions and equipment status. Next, a data-and-model layer embeds these signals within building geometry and analyses them using numerical models and AI-based methods. Finally, a decision-and-action layer translates analytical outputs into occupant guidance, control scenarios for building systems, and information for emergency responders. Whether a system can truly be characterised as dynamic depends on the efficiency of this pathway, including information flow speed, the ability to update scenarios during an incident, and the feedback coupling between the physical facility and its digital representation.

In the remainder of the paper, the DFS perspective serves as a common descriptive language for the three analysed facilities. Rather than treating them as independent research projects, the framework makes it possible to identify which parts of the sensor-to-decision chain are mature in each case and which remain less developed. This facilitates comparison between the research building in Lille, the medical-rescue facility in Beijing, and the shopping mall in Taipei 101, despite differences in scale, function, and context. The framework also supports recommendations, enabling the identification of specific DFS components that may inform Polish design and operational practice for buildings corresponding to ZL I, ZL II, and ZL III categories.

2.2. BIM in Fire-Safety Design

In this context, BIM should not be understood merely as an "attractive 3D model", but as a comprehensive digital representation of the facility. A frequently cited definition by the National Institute of Building Sciences emphasises that BIM provides a digital description of both physical and functional characteristics of a facility, serving as a shared knowledge resource throughout its life cycle and supporting decision-making from conceptual design to operation [1]. In other words, BIM integrates geometry, spatial relationships, material information, technical parameters of building systems, and data on facility use within a coherent model accessible to multiple disciplines.

Almatared and co-authors note that BIM—alongside IoT, AI, and AR—constitutes a foundation for developing digital twins in safety-management contexts, as it enables structured collection,

doi:10.20944/preprints202602.0570.v1

storage, and processing of facility information [1]. BIM's information management capabilities—data storage, extraction, and querying—allow it to function as a fire-safety knowledge base feeding analysis and visualisation systems. In fire-risk management, BIM therefore provides not only geometric context, but also an environment to encode compartments, fire-resistance classes, fire-fighting equipment, and system control scenarios.

Wehbe and Shahrour emphasise that BIM is useful in risk management and emergency-related actions [2]. In their review, BIM supports occupant localisation and tracking, near-real-time evacuation route generation, and occupant guidance via visualisation tools and mobile applications. Other studies have used BIM environments to develop virtual training settings, support continuous fire-situation monitoring, and automatically verify evacuation layouts against regulatory requirements [2]. These findings indicate that BIM increasingly functions as a shared reference platform for designers, fire-safety specialists, and facility operators.

Broader BIM reviews (beyond fire safety) highlight similar patterns. Azhar notes that BIM reshapes design workflows by improving information consistency, reducing clashes, and enabling interdisciplinary coordination, while also introducing organisational and competency challenges [3]. Volk et al. demonstrate the potential of BIM for existing buildings, provided that data are maintained appropriately [4]. Tang et al. describe BIM integration with IoT devices as a natural step towards more "living" models that extend beyond design and are continuously fed with operational data [5].

In this paper, BIM is therefore treated as a digital knowledge base in which geometry, structure, building systems, and fire-protection provisions are linked within a single model. On this foundation, subsequent analytical and operational layers can be developed, including CFD-based fire simulations using Fire Dynamics Simulator (FDS), evacuation modelling, AI-based algorithms, and ultimately a digital twin of the facility.

2.3. Digital Twin for Fire Safety

In Fire Safety Engineering, a digital twin (DT) is primarily a tool for continuous supervision of a building's fire-safety performance, rather than another 3D visualisation. Almatared et al. state that digital twins can be understood as dynamic digital models fed with data from FDAS, VAS, BMS, and IoT networks, supporting safety decision-making both during routine operation and during actual fire incidents [1]. The objective is not to create an additional static model, but to ensure that the computational representation of the building remains continuously informed about installed systems and occupant-related conditions.

In this framing, a DT integrates multiple layers. On the one hand, there is a geometry-and-information layer based on BIM, containing fire compartments, fire zones, fire-protection devices, and system control scenarios. On the other hand, there are data streams from smoke and temperature detectors, FDAS control panels, BMS platforms, and additional IoT sensors. Almatared shows that coupling these elements supports the establishment of a "fire safety digital twin", which monitors equipment status, records alarm events, links them to specific spaces, and provides unified dashboards for operators [1]. Khajavi et al. further argue that a safety digital twin can accompany a building throughout its life cycle and support rapid identification of safety deficits at any location and time [6].

A second dimension involves fire-state estimation. Zhang et al. demonstrate an approach where a dense temperature sensor array continuously provides data, while a neural network reconstructs a virtual representation of the fire, including estimates of heat release and fire origin [7]. Instead of a binary "fire/no fire" signal, such systems can generate a spatially meaningful representation of incident development and link it to operational decisions.

Digital twins increasingly extend beyond equipment and fire dynamics to include occupant behaviour and evacuation processes. Lin proposes a "digital twin of buildings and occupants" approach, in which a building model is accompanied by an occupant model informed by localisation systems, presence sensors, and crowd-movement modelling [8]. During an incident, these systems can update smoke, temperature, and occupancy conditions along evacuation routes and compute escape paths that avoid hazardous zones and congestion.

A shared characteristic across these studies is closed-loop logic: physical facility → sensing → modelling → decision → action → renewed sensing. Khajavi et al. describe this in a life-cycle context, where operational data feed the twin, analyses support decision-making, and results return as updated system settings, revised procedures, or retrofit strategies [6]. This continuous feedback loop differentiates a DT from traditional design-stage analyses: whereas FDS-based simulations and evacuation studies typically end with a report, a DT is intended to evolve with the facility throughout its operational life [1].

2.4. IoT and AI in Fire Detection and Evacuation

IoT and AI are increasingly integrated into fire safety, as traditional detection infrastructure evolves into dense sensor networks and adaptive machine-learning models operating under real-world conditions. Reviews focusing on IoT in fire-protection systems indicate that primary applications include early detection, localisation of the fire source, and near-real-time evacuation support [9,10].

The role of IoT in detection is relatively direct. Instead of individual detectors operating independently, distributed sensor networks measure multiple variables simultaneously—smoke, temperature, toxic gases, and camera-based inputs—and transmit data to supervisory platforms. AlQahtani et al. report that such systems may improve detection speed, localise the fire source more accurately, and reduce false alarms by relying on multi-sensor patterns rather than single-threshold triggers [9]. Similar findings appear in Yıldız’s review of ML in fire safety, where IoT provides the fundamental data layer enabling predictive modelling [10].

These outputs can be linked to control actions such as activating or adjusting smoke-control modes, compartmentalising the facility, isolating services, and designating hazardous areas. In near real time, systems may compute safer egress routes by considering not only distance but also corridor capacity and congestion, then communicate guidance via intelligent evacuation indicators. Reported outcomes include reductions in evacuation time and improved distribution of occupant flows compared with conventional guidance relying solely on the nearest-exit principle [11]. Lin extends this approach to multi-storey buildings, in which dense sensing informs continuous updates to directional signage logic [8].

Recent research increasingly emphasises that these solutions—from IoT-enabled detection to dynamic occupant guidance—should be treated as a continuous chain: sensors acquire data, AI algorithms interpret evolving conditions, and evacuation systems respond by updating signage directions, triggering VAS messages, or issuing occupant notifications [9,10]. Almatared argues that within a fire-safety digital twin, IoT and AI are key enabling mechanisms: without IoT/AI connectivity, the twin remains largely static; with them, it can monitor system status, anticipate incident development, and adapt evacuation strategies [1].

2.5. Dynamic Fire-Safety System in Responsive Architecture

Within responsive architecture, a Dynamic Fire-Safety System (DFS) enables a building to react to hazards in real time. On the one hand, it provides data through dense sensor networks and signals derived from FDAS, VAS, BMS, and IoT layers, integrated within a DT environment. On the other hand, it enables action: adjusting smoke-control strategies, controlling fire doors and smoke dampers, updating evacuation directions, and modifying user communications. Almatared indicates that a fire-safety digital twin supported by IoT data and AI algorithms can provide continuous monitoring, hazard diagnosis, and near-real-time decision support [1].

Yıldız describes buildings capable of modifying behaviour during operation depending on environmental and occupancy conditions [10]. Under normal conditions, responsiveness supports comfort and resource optimisation. During emergencies, however, the same principles can be reoriented toward life safety: the building observes incident development, evaluates possible

doi:10.20944/preprints202602.0570.v1

scenarios, and guides occupants to maximise the likelihood of safe egress. Fire safety therefore represents a domain in which responsive architecture becomes operationally critical, as system responsiveness directly affects evacuation performance and safety outcomes.

3. Research Methodology

3.1. Research Design: Multiple Case-Study Approach

The study adopts a multiple case-study methodology. Rather than proposing another theoretical model developed "on paper", the analysis focuses on three real-world implementations of BIM-based workflows, digital twins (DTs), IoT sensor networks, and selected AI modules in facilities characterised by high responsibility for life safety. Each case is treated as an independent study, but examined using the same research questions and within a unified analytical framework.

For each facility, the starting point is the reconstruction of a conventional, prescriptive fire-safety model grounded in static evacuation scenarios. The analysis then documents how an additional BIM/DT/IoT/AI layer was introduced, including: (i) which data are acquired; (ii) how these data are processed; and (iii) how they influence evacuation decision-making and the control of fire-protection systems.

The comparison between static and dynamic approaches is intended to evaluate the rationale for implementing Dynamic Fire-Safety System (DFS) solutions. The objective is not limited to describing technologies; instead, it assesses whether a performance-oriented model based on BIM, DT, AI, and IoT provides greater flexibility, improved decision-relevant information, and a higher level of safety than traditional systems meeting only baseline regulatory requirements.

3.2. Case-Study Selection

Three facilities were selected for analysis: (i) a research and academic building in Lille, broadly comparable to the Polish occupancy category ZL I; (ii) the Beijing Capital Airport Emergency Center, corresponding to characteristics of ZL II facilities; and (iii) a shopping mall within the Taipei 101 high-rise complex, representing challenges typical of a mixed-use environment combining ZL I and ZL III characteristics. These buildings differ in scale, function, and DFS implementation strategies:

(a) a research and academic building in Lille (France), where BIM was used as the basis for evacuation modelling and simulation-supported decision-making at the design stage, including optimisation of evacuation-route layouts;

(b) the medical-care wing of the Beijing Capital Airport Emergency Center (China), where conventional fire-safety systems were integrated with an expanded IoT sensor network, edge computing, and AI-driven dynamic evacuation signage;

(c) a multi-storey shopping mall within the Taipei 101 high-rise complex (Taiwan), where an AI/IoT solution supports emergency scenario analysis through intelligent dynamic evacuation signage driven by temperature and smoke sensor data and governed by the ESP algorithm.

The cases intentionally differ in maturity. Lille represents a BIM-centred approach focused on design-stage analysis and scenario-based evacuation modelling. Beijing provides an IoT-oriented implementation targeting dynamic evacuation management in a medical facility, where conventional evacuation drills may be operationally constrained due to varying occupant mobility. Taipei 101 demonstrates how AI-based planning for fire safety in a large retail environment can be aligned with broader "smart city" logic.

3.3. Case-Study Analysis Procedure

Each case study is analysed through a repeatable sequence of steps. First, the facility is described synthetically, including its function, scale, user profile, and key elements of the conventional fire-safety system (FDAS, VAS, sprinkler systems, smoke control, and BMS). Next, the architecture of BIM/DT/IoT/AI solutions is described, with emphasis on information flows between devices, integration platforms, and personnel.

In the subsequent step, implemented solutions are mapped onto DFS layers: data acquisition, data processing and analytics (AI), decision support, and control/communication/actuation (e.g., signage). Where source material allows, performance parameters reported for dynamic solutions are compared, including evacuation time, exit utilisation, and responsiveness to atypical scenarios.

Finally, a cross-case comparative analysis is conducted. DFS-layer coverage in each facility is synthesised, and BIM/DT/IoT/AI elements that measurably strengthen the fire-safety model are identified.

3.4. Data Sources and Material Selection

The analysis of the three case studies is based exclusively on written sources available in open access. For Lille, the primary source is [2], which provides a detailed description of BIM-based system architecture, the scope of FDS simulations and agent-based evacuation modelling, and integration with building infrastructure.

For the Beijing Capital Airport Emergency Center, the key source is [12] describing the BIM/IoT/AI/DCA approach, complemented by review papers addressing IoT- and deep-learning-based solutions for fire detection. For the Taipei 101 shopping mall, publications by [8,13] were used.

In addition, review publications contextualise BIM, DT, IoT, and AI applications in fire safety and evacuation, including works by [1] and others relevant to safety-related digital twins and dynamic evacuation guidance.

Material selection was purposive. Only implementations reporting both technical aspects (architecture, data flows, computational models) and performance-related outcomes (tests, scenario simulations, or evacuation analyses) were included. Consequently, the paper focuses on concepts validated at least in environments approximating real operational conditions.

3.5. Methodological Limitations and Reliability of Conclusions

The methodology includes deliberate limitations. A primary limitation concerns the small number of analysed facilities and their specificity. All cases originate from countries with advanced technological and regulatory infrastructures. Therefore, findings cannot be transferred mechanically to other contexts, particularly to the Polish legal and organisational environment.

A second limitation stems from reliance on published data. The authors did not have access to internal documentation from the original research teams. As a result, parts of the conclusions are based on secondary interpretation of descriptions, diagrams, and results reported in the literature. This applies especially to quantitative comparisons of evacuation scenarios and assessments of AI/IoT reliability.

Despite these constraints, the selected cases represent well-documented BIM/DT/AI/IoT implementations in fire safety within existing facilities. This enables a credible demonstration of how DFS components can be applied in practice and what implications may arise if similar solutions were introduced under Polish conditions.

4. Results

4.1. Case Study 1—Research Building in Lille (France)

4.1.1. Reconstruction of the Static Evacuation Model

This case study examines a single floor of a university facility functioning as a laboratory with an office component in the ESPRIT building (University of Lille). The objective is to compare a conventional prescriptive fire-safety model with a “smart evacuation” solution based on BIM and a scenario database describing fire development and available safe egress conditions.

The analysis focuses on the fourth floor of the ESPRIT building, which accommodates the Laboratoire de Génie Civil et Géo-Environnement (LGCgE). The floor area is approximately 1256 m² and has a typical functional layout consisting of offices, technical spaces, a small kitchen, and sanitary facilities. Under normal operating conditions, approximately 50 occupants are present (staff, doctoral researchers, and technical personnel) [2].

Based on these conditions, the original authors reconstructed the floor geometry as a BIM model. The 3D model includes partitions, windows, essential equipment, and—most importantly from a fire-safety perspective—the arrangement of evacuation doors and the compartmentation layout. The BIM model serves as a shared data repository, providing geometry for FDS calculations and defining the evacuation network used in Pathfinder [2].

Two representative fire scenarios were defined: (1) a kitchen fire triggered by ignition of equipment (gas burner-related); and (2) a fire in an electrical distribution room resulting from installation failure. Ignition locations and three evacuation exits were marked on the plan, serving as base input for FDS [2].

Fire simulations were conducted for 900 s, recording parameters relevant to evacuation safety, including smoke-layer temperature, smoke density, visibility, and CO concentration at 1.69 m height [2].

Standard tenability criteria were applied. For occupants unfamiliar with the building, the visibility threshold was 13 m. The maximum allowable temperature in the occupied zone was 60 °C. A CO threshold of 2500 ppm was assumed but did not govern the analysed scenarios [2]. ASET was determined for each exit as the earliest time at which any tenability criterion was exceeded.

In the kitchen fire scenario, Exit 1 loses tenability first (ASET ≈ 27 s), followed by Exit 2 (≈203 s), while Exit 3 remains tenable until ≈337 s [2].

In Scenario 2 (electrical room fire), Exit 2 loses tenability first (ASET ≈ 80–90 s), followed by Exit 3, while Exit 1 remains available longest [2].

An agent-based evacuation model was developed in Pathfinder using consistent geometry. Fifty agents were distributed across rooms; mean walking speed was assumed as approximately 0.78 m/s (with dynamic adjustment under congestion). In the no-fire scenario, clearance time was ~54.5 s, while under fire conditions it increased to ~251.5 s [2].

This reconstructed model reflects a prescriptive paradigm: evacuation routes are predefined, signage is static, and FDS/Pathfinder serve as one-time verification tools. No dynamic layer exists for sensor-driven adaptation.

4.1.2. Scope of the Intelligent Evacuation System Implementation

The FDS + Pathfinder model was embedded into an intelligent evacuation system based on a five-layer architecture: physical layer, monitoring layer, smart platform layer, control and alarm layer, and intelligent services layer [2].

The physical layer corresponds to the building and its fire-protection installations. The BIM model encodes geometry, zoning, materials, and fire-protection equipment locations.

Environmental sensors were installed (e.g., temperature, humidity, indoor air quality), enabling combined static information and real-time indoor-condition monitoring [2].

The monitoring layer links sensor readings to BIM-based locations. When an event is detected, the system identifies its location in the 3D model and forwards data to the smart platform layer, which interprets conditions against a scenario database (FDS and evacuation simulations).

The smart platform layer combines a database of precomputed simulations with a Dynamo toolchain and an AI/ML module that supports inference regarding safer routes under specific threat patterns [2] *(Wehbe and Shahrour, 2021)*.

The control/alarm and intelligent services layers provide an operator interface for monitoring, route recommendation, and occupant guidance.

4.1.3. System Effects and Simulation Results

The Lille case demonstrates that evacuation outcomes change substantially when fire effects are considered and when the system can redirect occupants away from unsafe exits. Under normal conditions, evacuation time is ~54.5 s; under fire constraints, it increases beyond 200–250 s [2].

Exit utilisation shifts with time-dependent tenability. For the kitchen scenario, Exit 1 usage drops significantly when fire effects are included, reflecting early loss of tenability.

A similar avoidance pattern occurs in the electrical room fire scenario, where Exit 2 becomes unavailable after ASET expiry.

Overall, these results highlight that evacuation performance cannot be reliably assessed through geometry-driven routing alone, as exit viability is strongly shaped by time-dependent fire conditions. The findings also suggest that integrating BIM-based spatial logic with scenario-informed decision support enables a qualitatively different evacuation strategy, where route selection is constrained by evolving tenability rather than static shortest-path optimisation. Consequently, the Lille case provides evidence that even a prototypical intelligent evacuation framework may enhance operational robustness by mitigating the risk of directing occupants toward progressively unsafe egress points.

4.2. Case Study 2—West Building of Beijing Capital Airport Emergency Center (BIM/IoT/AI/DCA), Beijing (China)

4.2.1. Reconstruction of the Static Evacuation Model

The second case study concerns the western wing of the Beijing Capital International Airport Emergency Center. This is a small healthcare facility located within the airport area, intended for handling emergency medical incidents involving staff and passengers, but without a typical inpatient ward component. The analysed area consists of the ground floor, including a reception area, medical offices, treatment rooms, and three main corridors. In total, the floor layout comprises 29 rooms organised in a corridor-based configuration [12].

When viewed exclusively through the lens of conventional fire-safety practice, the evacuation framework relies on static regulatory requirements. These typically specify minimum widths of evacuation routes and exits, maximum travel distances, and prescriptive evacuation time limits—up to 2 minutes for buildings with fire resistance classes I and II, and 1.5 minutes for class III [12]. Based on these rules, corridor layouts are designed, door widths are selected, and fixed evacuation signage is installed.

In such an approach, evacuation routing is commonly represented by the Dijkstra algorithm [12]. The building is modelled as a fixed network of nodes (doors, corridors, and exits) connected by edges. The objective of the algorithm is to identify the shortest geometric path from a given point to an exit (not necessarily the safest one). This routing logic does not account for fire growth, smoke spread, or the accumulation of occupants in narrow locations—conditions that frequently trigger panic, backtracking behaviour, and, consequently, loss of crowd control. This norm-compliant configuration—static signage and geometry-driven routes—is therefore adopted in the subsequent analysis as the “rigid” reference model for the case study. Only against this baseline can the impact of integrating BIM, IoT, AI, and dynamic evacuation signage be clearly demonstrated.

4.2.2. Scope of the Intelligent Evacuation System Implementation (BIM/IoT/AI/DCA)

The authors propose replacing the conventional evacuation information system with an intelligent guidance framework integrating a BIM model, an IoT sensor network, CCTV cameras equipped with AI-based functions, sensor-data acquisition, and dynamic LED evacuation luminaires [12].

The overall system operates through five successive stages. The first stage is fire initiation within the building. In the second stage, fire detection is achieved through smoke and temperature sensors, complemented by video-based recognition using CCTV image analysis. In parallel, the system continuously counts occupants within designated zones and detects obstacles blocking corridors. Sensor data are pre-processed by STM32 microcontrollers installed on IoT boards and transmitted via LoRa modules to an edge-computing gateway (sensor-data acquisition and processing) [12] (Ji et al., 2022).

The evacuation modelling approach is based on a Dynamic Cellular Automaton (DCA). The building is represented as a two-dimensional grid of cells—an intentionally simplified digital twin derived from the BIM model. Each cell may represent a corridor segment, a wall, an evacuation exit, a fire source, or an individual occupant. The DCA model integrates three groups of factors: (i) distance to available exits, (ii) occupant density along potential routes, and (iii) fire-related information (fire-source location, blocked passages, and door widths). As a result, evacuation routes are not fixed, as in a classical shortest-path model; instead, they evolve over time as fire conditions and congestion patterns change.

If the fire blocks part of a corridor or if a given exit becomes overloaded, the potential field is recalculated and the model reroutes a portion of occupants toward alternative exits that are safer in time-dependent terms. The DCA routing results are subsequently transmitted to dynamic evacuation signs, which update arrow directions to reflect the currently recommended routes [12]. These components are integrated through the BIM model, which functions as a “digital map” supporting sensor and signage placement, room-layout generation, and result visualisation. The operator can monitor the floor plan in real time, observe the current fire-source location, crowd density, and the computed evacuation routes [12].

4.2.3. System Effects and Simulation Results

The proposed DCA model was first benchmarked against the Dijkstra algorithm under simplified scenarios and subsequently applied to the actual layout of the medical facility. In both cases, the building was discretised as a grid with a 0.2 × 0.2 m cell size. Occupant movement was modelled in parallel at each time step, where each cell could advance by one step or remain stationary [12].

Compared to the Dijkstra algorithm, under the same building layout and with 14 occupants evacuating simultaneously, the DCA model reduced evacuation time by 55 s. In the rigid static model, occupants are directed along the shortest geometric routes, which may generate congestion at exits. In contrast, the DCA approach considers not only distance but also crowding along corridors. Therefore, the system can reallocate part of the evacuees to alternative routes—sometimes longer in metric distance, yet faster in practice due to reduced congestion.

The authors examined multiple variants, including two alternative corridor configurations, three different fire-source locations, and a baseline drill scenario without fire conditions. Simulations were performed for two occupant groups (50 and 200 evacuees).

In conclusion, the results indicate that increasing exit width from 5 m to 10 m reduces evacuation times, particularly in the 200-person scenarios. Fire-source location also substantially affects performance, with unfavourable ignition points producing differences of several tens of seconds. Under the most demanding variants, the DCA-based routing supports compliance with prescriptive limits by maintaining evacuation times below 2 minutes [12].

The authors further report that dynamic guidance supported by intelligent signage reduced the average evacuation time in one scenario by up to 72% compared to evacuation using fixed static signs only. This suggests that transitioning from a purely “paper-based” evacuation design to active, dynamic control of signage can generate a substantial additional time margin for safe egress.

4.2.4. Conclusions from the Beijing Capital Airport Emergency Center Case Study

The Beijing Emergency Center case study complements the Lille example. While the Lille study demonstrates how BIM and an FDS/ASET-based scenario database can support operator decision-making, the Beijing case shifts the emphasis toward the executive layer of a dynamic fire safety system. Here, the system does not end at analysis; it directly controls evacuation signage within the building [12].

In conventional evacuation models, fixed signage and shortest-path routing defined by the Dijkstra algorithm are typically assumed to be sufficient. The study by Ji et al. shows that under real-world constraints—such as varying fire-source locations, heterogeneous walking speeds, and localised congestion—an approach in which evacuation routes are updated dynamically provides superior safety performance. The system can automatically reroute occupants from a shorter but threatened path toward a longer yet safer alternative, which may ultimately reduce total evacuation time.

A second key conclusion concerns technological integration. Within this relatively small facility, the authors successfully combined a BIM model, an IoT sensor network, CCTV cameras with image analysis, an edge-computing gateway (for sensor aggregation and processing), and dynamic LED signage. Together, these components form a practical evacuation-oriented digital twin module operating in near-real time and implementing an integrated event cycle consistent with the DFSS model proposed in this article.

The authors also acknowledge that their model remains simplified. Fire is treated primarily as a source that blocks segments of corridors, and multi-storey evacuation is not addressed. Despite these limitations, the reported improvements—namely a 55 s reduction compared to Dijkstra-based routing and up to a 72% reduction compared to static signage—indicate that BIM/IoT/AI components can go beyond reproducing traditional solutions in digital form and can meaningfully increase the time-based safety margin within an existing medical facility [12].

Building on the Beijing Capital Airport Emergency Center case study, which demonstrates near-real-time route updating through BIM/IoT/AI integration and Dynamic Cellular Automaton (DCA) modelling combined with dynamic LED signage actuation, the next case study extends the DFSS logic to a significantly larger and more complex public environment. The Taipei 101 shopping mall exemplifies a multi-level, high-occupancy setting where evacuation robustness depends not only on hazard-aware routing but also on scalable human–system communication mechanisms. In this context, dynamic evacuation signage becomes the primary interface enabling system-level guidance without relying on individual occupant tracking or smartphone-based applications [8,13].

4.3. Case Study 3—Taipei 101 Shopping Mall (IIFESS/ESP)

Case Study 3 investigates a high-occupancy, multi-level shopping mall environment, where evacuation performance is shaped not only by building geometry and code-compliant egress capacity, but also by the dynamic interaction between fire growth, smoke propagation, and congestion formation. Unlike smaller or semi-controlled facilities, large retail spaces introduce additional constraints, including heterogeneous occupant behaviour, uneven spatial distribution of crowds, and limited feasibility of user-dependent technologies such as smartphone-based evacuation applications.

In this context, the Taipei 101 case provides an illustrative example of a scalable DFSS-compatible strategy based on the Intelligent IoT-enabled Fire Evacuation Signage System (IIFESS) and the associated Evacuation Strategy Planning (ESP) algorithm. The core contribution of this approach lies in transforming evacuation signage from a passive, static compliance element into an active executive component capable of updating guidance directions in response to evolving tenability and congestion patterns [8,13].

4.3.1. Reconstruction of the Rigid Fire-Safety Model

In the conventional approach, fire safety in a three-storey shopping mall forming part of a high-rise building relies primarily on the fire alarm system, sprinkler installation, fixed evacuation signs, and prescriptive requirements regarding the number and distribution of evacuation routes. According to Taiwanese regulations, high-rise buildings must provide at least two independent evacuation routes, while large shopping malls require more than two evacuation doors per storey. In Taipei 101, these requirements are fulfilled, as the shopping mall provides four main exits [8,13].

Within this “rigid” model, evacuation signage is entirely static. Arrows permanently indicate the nearest exit. The system does not respond to fire growth or increasing smoke accumulation, nor does it account for congestion in staircases or corridors. If a fire disables one of the exits, occupants may still be guided toward zones exposed to smoke or elevated temperature.

doi:10.20944/preprints202602.0570.v1

This static evacuation signage and purely geometry-driven routing represent the baseline reference condition for the subsequent analysis of the Taipei 101 case.

4.3.2. Scope of the Intelligent Evacuation System Implementation

In the Taipei 101 case, conventional fixed evacuation signage was replaced by a system referred to as the Intelligent IoT-enabled Fire Evacuation Signage System (IIFESS). In practice, this means that the arrow displayed on an evacuation sign is no longer static but can change direction during a fire depending on fire and smoke conditions and on the formation of congestion [8,13].

The system is supported by a network of smoke and temperature sensors installed on each floor of the shopping mall. Standard fire detectors are used, but they are embedded within an IoT-based architecture. At defined time intervals (the authors provide a one-minute example), measured values are transmitted to the IIFESS server using wired or wireless communication, depending on the installed system [8,13]. Data are collected in fixed time intervals (time slots), enabling the system to maintain an up-to-date situational picture. At each time slot, the system knows which sections of evacuation routes remain tenable and which areas experience hazardous temperature or smoke conditions.

The core of the solution is the IIFESS server running the proposed dynamic evacuation routing algorithm. The algorithm represents the building as a graph, where nodes correspond to doors, corridor intersections, staircases, and evacuation exits, while edges represent traversable route segments between nodes [8,13]. At each node, several types of information are stored: baseline travel time under non-hazard conditions, indicators associated with temperature and smoke exposure, and an additional congestion-related component referred to as the congestion danger index.

Real-time hazard-related information is computed using FDS 7.9.1 (Fire Dynamics Simulator) developed by NIST (USA). A 3D building model similar to a BIM representation is used to derive real-time distributions of temperature, smoke, visibility, gas flow velocities, and toxic gas concentrations. Based on these outputs, the server updates ASET/RSET conditions and can support the control of smoke management and ventilation as well as safe-route recommendations.

At each iteration, the algorithm verifies whether safe routes still exist between each sign and each available exit, i.e., routes where temperature and smoke levels remain below defined safety thresholds [8,13]. If a route violates the thresholds, it is excluded from further consideration. In addition, the ESP algorithm attempts to avoid routes likely to become congested. Unlike systems based on mobile applications, it does not track the location of each individual occupant. Instead, when a corridor segment is predicted to lose flow capacity, the system artificially "penalises" it in routing calculations, treating it as less favourable even if it is geometrically short. As a result, the algorithm selects routes that may be longer in distance but allow faster and smoother crowd movement [8,13].

A key advantage is that the system does not require individual occupant localisation. Rather than relying on smartphone-based guidance, it communicates solely through dynamic signage mounted on walls and above doors. This is consistent with the operational reality of large shopping malls, where most customers do not have a dedicated evacuation application, but all occupants can see flashing green evacuation signs indicating a safe exit path.

4.3.3. System Effects and Simulation results of the Intelligent Evacuation System (IIFESS, IoT, FDS, ESP)—condensed

The performance of the IIFESS framework in the Taipei 101 shopping mall was evaluated through simulation-based validation using FDS 7.9.1. The model incorporated a dense sensing layer (smoke and temperature detectors) and sprinkler configurations to generate time-dependent hazard fields for temperature, smoke, visibility, and toxic exposure. Two representative fuel scenarios—methane- and PVC-related fires—were analysed to represent distinct hazard profiles and tenability degradation mechanisms [8,13].

The authors compared three guidance strategies: (i) Random Selection (RS), representing behaviour under static signage with quasi-random route choice; (ii) FEL, which reacts to fire conditions using sensor/FDS inputs but does not explicitly address congestion risk; and (iii) the proposed ESP algorithm, which dynamically assigns routes to each sign by simultaneously enforcing tenability constraints (thermal and smoke-related) and penalising segments prone to congestion through a congestion danger index (Yen and Lin, 2024). Across scenarios, ESP consistently outperformed RS and maintained a measurable advantage over FEL, particularly under high-occupancy and sprinkler-off conditions, where evacuation robustness depends strongly on the ability to avoid time-dependent route loss and bottleneck formation.

The results indicate that, under methane fire conditions with evenly distributed occupants, ESP yields substantially higher successful evacuation rates than both baseline strategies, and the performance gap persists even when sprinklers are enabled. Under PVC fire conditions, differences between ESP and FEL narrow but remain significant, while RS remains consistently unreliable. Importantly, the advantage of ESP becomes most pronounced in non-uniform occupant distributions, where local crowd concentration and fire initiation occur within the same zone, producing severe congestion and rapid tenability loss near the nearest exits. In these conditions, dynamic signage control supported by ESP improves the allocation of evacuees across alternative exits and reduces exposure to hazardous segments compared to static guidance.

Overall, these findings suggest that the core benefit of IIFESS lies not in shortest-path optimisation but in real-time feasibility filtering of evacuation routes under evolving tenability constraints, combined with congestion-aware route penalisation. Consequently, IIFESS/ESP enhances evacuation robustness at the scale of a multi-level retail environment by transforming evacuation signage from a passive compliance element into an active executive component of a dynamic guidance loop [8,13].

Table 1. Comparative characteristics of evacuation guidance strategies in the Taipei 101 case study.

Strategy	**Core principle**	**Uses hazard information (temperature/smoke)**	**Accounts for congestion**	**Guidance medium**	**Expected performance under high occupancy / uneven distribution**
RS (Random Selection)	Quasi-random choice under static signs	No	No	Fixed signage	Low; prone to unsafe routing and bottlenecks
FEL	Hazard-responsive routing (sensor/FDS-driven)	Yes	Limited / indirect	data	Moderate; improves over RS but vulnerable to congestion
ESP (IIFESS)	Tenability-filtered + congestion-penalised dynamic routing	Yes (explicit constraints)	Yes (congestion danger index)	data	High; most robust in complex and non-uniform scenarios

4.3.4. Conclusions from the Taipei 101 Case Study Analysis

The Taipei 101 case study demonstrates that building geometry and compliance with prescriptive requirements are insufficient for ensuring evacuation robustness in a large, multi-level shopping mall. Static evacuation signage performs adequately mainly under simplified conditions with uniform occupant distribution and limited congestion. However, when a real incident occurs, fire dynamics (temperature rise, smoke spread, progressive route disabling) and variable-density crowd behaviour cause this rigid model to become increasingly unreliable.

The case study shows that, at this scale, a system capable of recalculating available routes in near-real time and updating signage instructions provides a substantially more effective approach. A second critical contribution concerns the user-interface strategy. Instead of assuming that all customers will install a smartphone-based application, the authors shift the entire communication burden onto intelligent evacuation signage. The system operates at a level already required by regulations (signs installed above doors and in corridors), yet it assigns them a new function: transforming passive pictograms into active executive devices of a dynamic evacuation system.

Together with sensor data and simulation-derived hazard maps, this results in a practical "sense–decide–guide" cycle. Detectors and simulations generate a dynamic hazard representation, the algorithm selects safer routes, and signs immediately update guidance directions. From an outcome perspective, the numerical results are unambiguous. In methane fire scenarios, ESP-based routing with dynamic signage increases the probability of successful evacuation by approximately 34% compared to the earlier FEL algorithm, while in PVC scenarios the advantage remains at the level of several to over ten percentage points. Importantly, the system can compute new signage configurations within a time shorter than the interval between consecutive sensor readings, indicating that it is not merely an offline modelling concept but a solution capable of operating during a fire event.

At the same time, the authors acknowledge key limitations, including the absence of individual occupant tracking and simplified congestion modelling. Despite these constraints, the Taipei 101 study provides strong evidence that dynamic control of evacuation signage in large commercial buildings can substantially increase evacuation safety margins.

4.4. Cross-Case Synthesis of Case Studies 1–3 in the DFSS Perspective

Taken together, the three case studies illustrate complementary layers of a Dynamic Fire Safety System (DFSS). The Lille case primarily demonstrates the analytical and decision-support layer, where BIM provides a shared geometric backbone and precomputed fire–evacuation scenarios enable time-dependent assessment of exit viability (ASET) and the feasibility of maintaining RSET below ASET. In contrast, the Beijing Emergency Center shifts the emphasis toward the executive layer, showing how a BIM/IoT/AI pipeline coupled with a Dynamic Cellular Automaton (DCA) can update routes in response to both hazard evolution and congestion and can physically actuate dynamic evacuation signage in near-real time. The Taipei 101 case extends this logic to a large-scale, multi-level public environment, where smartphone-based guidance is impractical and dynamic signage becomes the primary human–system interface. Across cases, a common conclusion emerges: geometry-driven shortest-path routing is insufficient under time-dependent tenability loss and crowd-induced bottlenecks; DFSS-oriented solutions improve robustness by integrating hazard-aware feasibility screening with adaptive allocation of evacuees across exits and corridors. Importantly, the cases also reveal a maturity gradient: from scenario-based decision support (Lille), through near-real-time sensing and actuation (Beijing), to system-level scalability in high-occupancy public settings (Taipei 101), collectively supporting the feasibility of incremental DFSS implementation in existing buildings.

5. Discussion

5.1. Cross-Case Comparison (Lille, Beijing, Taipei 101)

The three case studies illustrate distinct operational profiles of BIM/DT/IoT/AI-supported Dynamic Fire-Safety Systems. In all cases, the primary departure from the rigid model lies in replacing static routing logic with time-dependent, hazard-informed guidance. However, the maturity and operational closure of the "sensor–analysis–decision–actuation" loop differs.

Lille primarily demonstrates a BIM-centred analytical environment, where simulation outputs form a scenario database enabling safer route inference [2]. Beijing implements a closed operational loop that actively controls dynamic signage in near real time [12]. Taipei 101 extends dynamic signage optimisation to very high-occupancy, multi-level conditions, combining FDS-derived hazard states with congestion-aware routing [8,13].

5.2. Responses to Research Questions

RQ1. Evidence across all three cases supports measurable safety improvements when moving from static to dynamic evacuation guidance. Lille highlights improved ASET/RSET margin awareness through scenario knowledge; Beijing demonstrates evacuation-time reductions via congestion-aware routing and dynamic signage; Taipei 101 demonstrates improved successful evacuation probability under high-density conditions [2,8,12].

RQ2. Although a single universal component set does not exist, the minimum functional pattern is consistent: sensing (FDAS/IoT/CCTV), modelling/analytics (simulation and/or AI), decision logic (routing), and actuation/communication (dynamic signage and/or operator guidance) [1,8,12].

RQ3. Transferability to Poland is technically feasible, but organisational and regulatory pathways remain the key barrier. Current Polish regulations focus on prescriptive requirements and do not formally recognise DFS components such as variable-direction signage or digital-twin-driven decision support as an alternative compliance route. A performance-based pathway would require defined equivalency criteria and formal validation procedures.

5.3. Implications for the Polish Fire-Safety System

The case studies indicate that BIM/DT/IoT/AI-based Dynamic Fire-Safety Systems can enhance occupant safety compared with static, prescriptive-only models. For the same building geometry, exit configuration, and formal compliance status, safety margins may be increased if evacuation routes adapt to evolving hazards rather than relying solely on fixed signage.

In the Polish system, current regulations define extensive prescriptive requirements (e.g., minimum exit widths, travel distances, compartmentation, fire resistance, signage rules). While compliance with these requirements provides a baseline, regulations do not explicitly address variable-direction evacuation signage, real-time routing algorithms, edge-computing integration with FDAS/VAS, or fire-safety digital twins.

The case studies suggest that Poland could maintain prescriptive requirements as a minimum baseline while enabling performance-based approaches in complex facilities. First, BIM-based evacuation modelling supported by CFD fire analysis and evacuation simulation could be formally recognised as an equivalency pathway for justified deviations. Second, Beijing and Taipei 101 indicate the need for a regulatory category of dynamic evacuation-control systems, including: acceptance of variable-direction signage, reliability and fault-tolerance criteria, emergency power supply requirements, and supervision/verification procedures. Third, as safety-related information increasingly resides in digital models, BIM/DT could evolve into formal carriers of fire-safety documentation, integrating conventional systems with dynamic control logic.

Implementation would benefit from structured pilot projects supported by guidance documents and verification protocols (FSE modelling, drills, and scenario-based evaluation). In summary, the Lille, Beijing, and Taipei 101 cases suggest that prescriptive compliance can remain a baseline, while a dynamic safety layer can be built above it. Enabling performance-based pathways, formalising dynamic evacuation-control systems, and recognising BIM/DT/IoT/AI as legitimate elements of design and operation would be key steps toward systematic DFS adoption in Poland.

6. Conclusions

The presented case studies confirm that Dynamic Fire-Safety Systems (DFS), based on BIM/DT/IoT/AI integration, are no longer solely a research concept, but solutions already being implemented in practice that can increase evacuation resilience in facilities with high life-safety responsibility. In each analysed facility, the key departure from the “rigid” model consisted in replacing geometry-driven logic and the nearest-exit principle with a time-dependent approach that accounts for tenability loss, variable exit availability, and congestion-induced bottlenecks. As a result, DFS does not so much “speed up” evacuation in a universal sense as it increases its reliability under uncertainty by reducing the risk of directing occupants onto routes that are already hazardous at a given moment or that, in practice, have lost throughput capacity.

The cross-case analysis further revealed a clear maturity gradient. Lille represents the analytical and decision-support layer, in which BIM and a database of fire–evacuation scenarios (FDS + evacuation simulations) support inference of safer routes. Beijing shifts the emphasis toward the executive layer, demonstrating a closed "sense–decide–actuate" loop and dynamic signage control in near real time. Taipei 101, in turn, evidences the scalability of the approach in multi-storey, high-occupancy environments, where the key human–system interface becomes dynamic signage rather than mobile applications. The shared conclusion is unambiguous: the shortest path is not synonymous with the safest path when evacuation conditions deteriorate over time and when the crowd itself generates critical bottlenecks.

From the perspective of implementation in Poland, the findings indicate the need to separate two compliance levels: a prescriptive minimum baseline and an admissible dynamic overlay under a performance-based framework. The current approach based on detailed requirements provides a reference point, but it does not establish a formal equivalency-assessment pathway for elements such as variable-direction signage, hazard-dependent routing algorithms, or an operationally used digital twin. If DFS is to become a practical tool (rather than merely a demonstrator), validation and reliability criteria must be defined, including fail-safe behaviour, emergency power-supply requirements, robustness to damage and data errors, rules for scenario-based testing, as well as acceptance procedures and periodic verification.

The limitations of the study should also be noted: the conclusions are based on secondary sources and on results reported by the authors of the analysed implementations, without conducting independent evacuation trials in these facilities. The next step should therefore involve pilot projects under Polish conditions, conducted in parallel with the development of assessment protocols (CFD/FDS + evacuation + functional testing of signage) and an analysis of human factors, because DFS effectiveness is sensitive to signal legibility, message consistency, and crowd behaviour. Only such an approach will translate the potential of BIM/DT/IoT/AI into a predictable, certifiable safety improvement in complex ZL I–III buildings and in transport and medical infrastructure.

Key conclusions:

1. DFS increases evacuation resilience by coupling hazard and congestion information with dynamic guidance, rather than by merely "shortening the route".
2. Dynamic signage provides a practical, scalable interface in high-occupancy facilities where personalised guidance (e.g., apps) may be unrealistic.
3. Transfer to Poland is technically feasible, but requires a formal performance-based pathway and equivalency criteria with validation procedures.
4. Implementation priorities should include pilot deployments and reliability-assessment standards (fail-safe, emergency power supply, scenario testing, periodic BIM/DT model verification).

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;
ASET	Available Safe Egress Time;
BIM	Building Information Modelling;
BMS	Building Management System;
CCTV	Closed-Circuit Television;
CFD	Computational Fluid Dynamics;
DCA	Dynamic Cellular Automaton;
DFS	Dynamic Fire-Safety System;
DT	Digital Twin;
FDAS	Fire Detection and Alarm System;
FDS	Fire Dynamics Simulator;
FEL	Fire-Effect-Location (algorithm);
FED	Fractional Effective Dose;
FSE	Fire Safety Engineering;
IoT	Internet of Things;
MCP	Manual Call Point;
ML	Machine Learning;
PBD	Performance-Based Design;
RS	Random Selection;
RSET	Required Safe Egress Time;
VAS	Voice Alarm System.

References

1. Almatared, M.; Liu, H.; Abudayyeh, O.; Hakim, O.; Sulaiman, M. Digital-Twin-Based Fire Safety Management Framework for Smart Buildings. ***Buildings*** 2023, *14*, 4. https://doi.org/10.3390/buildings14010004
2. Wehbe, R.; Shahrour, I. A BIM-Based Smart System for Fire Evacuation. ***Future Internet*** 2021, 13, 221. https://doi.org/10.3390/fi13090221

3. Azhar, S. Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry. ***Leadership and Management in Engineering*** 2011, *11*, 241–252. https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127
4. Volk, R.; Stengel, J.; Schultmann, F. Building Information Modeling (BIM) for Existing Buildings—Literature Review and Future Needs. ***Automation in Construction*** 2014, *38*, 109–127. https://doi.org/10.1016/j.autcon.2013.10.023
5. Tang, S.; Shelden, D.R.; Eastman, C.M.; Pishdad-Bozorgi, P.; Gao, X. A Review of Building Information Modeling (BIM) and the Internet of Things (IoT) Devices Integration: Present Status and Future Trends. ***Automation in Construction*** 2019, *101*, 127–139. https://doi.org/10.1016/j.autcon.2019.01.020
6. Khajavi, S.H.; Tetik, M.; Liu, Z.; Korhonen, P.; Holmström, J. Digital Twin for Safety and Security: Perspectives on Building Lifecycle. ***IEEE Access*** 2023, *11*, 52339–52356. https://doi.org/10.1109/ACCESS.2023.3278267
7. Zhang, C. Review of Structural Fire Hazards, Challenges, and Prevention Strategies. ***Fire*** 2023, *6*, 137. https://doi.org/10.3390/fire6040137
8. Lin, J.R. Digital Twin of Buildings and Occupants for Emergency Evacuation: Framework, Technologies, Applications and Trends. ***Advanced Engineering Informatics*** 2025, 103419. https://doi.org/10.1016/j.aei.2025.103419
9. AlQahtani, A.A.S.; Sulaiman, M.; Alshayeb, T.; Alamleh, H. From Inception to Innovation: A Comprehensive Review and Bibliometric Analysis of IoT-Enabled Fire Safety Systems. ***Safety*** 2025, *11*, 41. https://doi.org/10.3390/safety11020041
10. Yıldız, M.A. Machine Learning for Fire Safety in the Built Environment: A Bibliometric Insight into Research Trends and Key Methods. ***Buildings*** 2025, *15*, 2465. https://doi.org/10.3390/buildings15142465
11. Nguyen, V.-Q.; Vu, H.-T.; Nguyen, V.-H.; Kim, K. A Smart Evacuation Guidance System for Large Buildings. ***Electronics*** 2022, *11*, 2938. https://doi.org/10.3390/electronics11182938
12. Ji, Y.; Wang, W.; Zheng, M.; Chen, S. Real Time Building Evacuation Modeling with an Improved Cellular Automata Method and Corresponding IoT System Implementation. ***Buildings*** 2022, *12*, 718. https://doi.org/10.3390/buildings12060718
13. Yen, H.-H.; Lin, C.-H. Intelligent Evacuation Sign Control Mechanism in IoT-Enabled Multi-Floor Multi-Exit Buildings. ***Sensors*** 2024, *24*, 1115. https://doi.org/10.3390/s24041115