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State-of-the-Art overview

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1 Introduction

Fire safety engineering plays a critical role in safeguarding building occupants and enhancing the resilience of the built environment. Traditionally, fire safety has been addressed through a combination of prescriptive regulations and performance-based engineering methods. These approaches are often applied late in the design process and supported by specialist tools that remain largely disconnected from mainstream building design workflows. In parallel, the Architecture, Engineering and Construction (AEC) sector has undergone rapid digital transformation, driven by the widespread adoption of Building Information Modelling (BIM) as a central platform for design, coordination, and information management throughout the building life cycle.

Despite the extensive uptake of BIM for applications such as geometric coordination, quantity take-off, cost estimation, and energy analysis, the integration of fire safety engineering into BIM-based workflows remains limited and fragmented. Fire safety requirements are frequently interpreted manually, documented in separate reports, or verified using stand-alone analysis tools that rely on manual data exchange. This separation results in inefficiencies, an increased risk of inconsistencies, and missed opportunities for early-stage design feedback—where fire safety considerations can have the greatest impact at the lowest cost.

In recent years, growing regulatory pressure, increasing building complexity, and advances in digital technologies have renewed interest in the digitalisation of fire safety processes. Open standards such as Industry Foundation Classes (IFC), Information Delivery Specifications (IDS), and the BIM Collaboration Format (BCF), together with national and international regulatory frameworks, provide a foundation for more structured, interoperable approaches to fire safety compliance and analysis. In parallel, both research and industrial innovation have explored automated compliance checking, fire and evacuation simulation, artificial intelligence, and digital twin concepts as means to improve the reliability, transparency, and efficiency of fire safety design and verification.

The FireBIM project addresses these challenges by aiming to integrate fire safety requirements and verification more effectively into BIM-based workflows, with particular emphasis on early design stages, interoperability, and regulatory relevance. As a foundation for this effort, this deliverable presents a comprehensive State of the Art (SotA) overview of fire safety engineering in the context of BIM and related digital technologies. The purpose of the document is not only to summarise existing research and industrial solutions, but also to identify limitations, gaps, and opportunities that are directly relevant to the objectives of the FireBIM project.

The document begins by establishing the necessary background, outlining key concepts, regulatory contexts, and fire safety challenges within the built environment. It then reviews the current state of the art in BIM-based fire safety engineering, covering both prescriptive and performance-based approaches, digital compliance checking, simulation, data interoperability, and emerging technologies such as artificial intelligence and digital twins. Industrial applications and national initiatives are analysed alongside academic research to highlight differences in maturity and adoption. Finally, the deliverable synthesises key research gaps and challenges and outlines a roadmap to inform subsequent FireBIM developments.

As such, this State-of-the-Art report serves as a baseline reference for the FireBIM project, ensuring a shared understanding of the current technological and regulatory landscape and providing a structured basis for innovation, validation, and future harmonisation efforts.

2 Background

Present the fire safety background and digital/BIM background:

- Definitions (Fire Safety Engineering, BIM, Compliance, etc.)
- Regulatory Context and Standards (IFC, IDS, BCF, National Codes)

Overview of Fire Safety Challenges in the Built Environment

Fire Safety Engineering (FSE) relies on the application of scientific principles to analyze and design solutions aimed at ensuring occupant safety and structural resistance to fire. Building Information Modeling (BIM), meanwhile, is a digital approach to creating and managing intelligent representations of buildings throughout their life cycle. These two disciplines converge in the quest for compliance with regulatory requirements and technical standards.

In terms of standards, formats such as IFC (Industry Foundation Classes)**Fejl! Henvisningskilde ikke fundet.**, IDS (Information Delivery Specification) [1],**Fejl! Henvisningskilde ikke fundet.**, and BCF (BIM Collaboration Format) **Fejl! Henvisningskilde ikke fundet.** promote data interoperability and traceability, while national codes and European directives define performance and safety criteria. In Belgium, for example, the Royal Decree of July 7, 1994, **Fejl! Henvisningskilde ikke fundet.**on basic fire prevention standards for buildings imposes specific requirements on the fire resistance of load-bearing elements and compartmentalization, which must be integrated from the design stage onwards.

It is crucial that fire safety is taken into account from the earliest stages of the project, as architectural choices, materials, and technical systems directly influence compliance and performance in the event of a fire. Late integration leads to additional costs and risks of non-compliance.

Despite these advances, challenges remain: regulatory complexity, data heterogeneity, integration of fire scenarios into BIM models, and a lack of automated tools to verify compliance. These issues are particularly critical in a built environment where density, material diversity, and changing uses increase risks and the need for a robust digital approach.

3 State of the Art in Fire Safety Engineering in Building Information Modeling

This chapter presents the state of the art in the integration of fire safety engineering (FSE) within Building Information Modeling (BIM)–based workflows. It reviews how current research and industrial practice address fire safety requirements using digital building models, with particular attention to interoperability, automation, and regulatory compliance. The chapter covers both prescriptive and performance-based approaches, highlighting the extent to which fire safety considerations are embedded in BIM environments across different stages of the building life cycle. By synthesising recent academic studies, standards, and implemented systems, the chapter establishes a baseline for assessing current capabilities and identifying limitations relevant to the objectives of the FireBIM project.

3.1 BIM and Fire Safety Engineering Integration

Building Information Modelling (BIM) has become a central enabler of digital transformation in the architecture, engineering, and construction (AEC) sector due to its capacity to manage and exchange information across disciplines and throughout the building life cycle. However, fire safety engineering (FSE) has historically been late and reluctant in its integration into building design (Dederichs and Karlshøj, 2015) [4] and remains weakly integrated into BIM-based workflows. Fire safety analyses therefore often rely on specialist tools and manual data transfer rather than seamless digital integration. Comprehensive reviews confirm that this lag is not due to a lack of technical potential, but rather to fragmentation in data standards, limited interoperability, and discipline-specific modelling practices.

Several review studies have been published in recent years (REF). The review by Malagnino et al. (2022) [6] provides a decade-long synthesis of BIM–FSE research and shows that many studies focus on isolated analytical tasks rather than holistic life-cycle integration. While BIM is widely adopted for geometric coordination, cost estimation, and energy analysis, its application to fire safety remains largely confined to downstream simulation and visualisation tasks, often detached from early design decision-making.

Dederichs and Karlshøj (2015) argue that BIM has the potential to enable the early integration of fire safety considerations into the design process. In line with this, Davidson and Gales (2021) [7]later highlight that meaningful BIM–FSE integration requires early involvement of fire engineers as well as significantly higher levels of detail (LOD) in fire-relevant objects. Such requirements, however, are frequently incompatible with prevailing design practices and commercial constraints.

Fire safety design approaches can generally be subdivided into two categories: prescriptive approaches, based on national codes and regulatory frameworks, and science-based performance-based methods, which complement traditional prescriptive rules. From a BIM perspective, both approaches ultimately need to be addressed and supported within digital workflows (Akbar & Hassanain, 2023) [8]. Nevertheless, the majority of BIM-related fire safety research and development to date has focused primarily on performance-based approaches, which are therefore addressed in the following sections.

3.2 Fire Simulation and Evacuation Modelling

The most mature and extensively researched application area of BIM in fire safety engineering (FSE) is the simulation of fire dynamics and evacuation, used to predict fire development on the one hand and the evacuation of occupants from buildings on the other. Scoping and systematic reviews show that the majority of BIM-enabled fire safety applications focus on linking BIM models to computational tools such as CFD-based fire models and agent-based evacuation simulators. Akbar and Hassanain's [8] scoping review from 2023 of 37 studies spanning more than two decades confirms that BIM-based evacuation modelling has reached a relatively high level of technological readiness yet remains methodologically fragmented and tool-dependent.

Recent work has increasingly addressed interoperability challenges in evacuation workflows. In 2023 Yakhoua et al. **Fejl! Henvisningskilde ikke fundet.** present Evac4BIM, which enables bidirectional data exchange between Autodesk Revit and Pathfinder, allowing both geometric data and simulation results to be transferred back into the BIM environment. This two-way integration represents a significant step beyond one-directional export workflows and improves traceability and design feedback loops. Nevertheless, native software formats still dominate data exchange, and reliance on proprietary application programming interfaces (APIs) continues to limit scalability and long-term reproducibility.

3.3 Performance-Based Fire Safety and Data Interoperability

Performance-based fire safety design poses additional challenges for BIM integration due to its reliance on quantified risk metrics, scenario-based analysis, and iterative simulation. In 2021 Siddiqui et al. [9] identify critical shortcomings in open BIM standards, particularly Industry Foundation Classes (IFC), which lack a dedicated data model for fire safety engineering (FSE) and provide only limited mechanisms for storing analysis results, assumptions, and verification data. As a result, performance-based workflows often depend on external documents and spreadsheets, undermining the concept of a continuous digital information chain.

Despite these limitations, research has begun to explore structured approaches for embedding fire risk assessment within BIM environments. In 2025 Terzi et al. [10] proposed a BIM- and GIS-based multi-criteria decision-making framework (TOPSIS) to assess indoor fire risk spatially in three dimensions. This approach demonstrates the potential for combining BIM geometry with quantitative risk indicators and visualisation techniques, although it remains primarily research-driven and requires further validation in professional practice.

The terminology underpinning performance-based fire safety design is formally defined and harmonised in ISO 13943: Fire safety — Vocabulary [11],[12]**,** which provides a common and internationally accepted conceptual foundation for fire safety engineering. This standard establishes a clear baseline for the consistent interpretation of fire safety concepts and performance metrics, which is essential for analytical and simulation-based design approaches. However, while this terminology supports the structuring of BIM-based performance-oriented workflows, it is not directly applicable to prescriptive design, where compliance is determined by deterministic regulatory requirements rather than standardised performance definitions. Consequently, BIM representations aligned with ISO

13943 terminology cannot be directly reused for prescriptive code checking without additional rule and terminology formalisation and regulatory interpretation.

3.4 Prescriptive Regulation and Digital Code Compliance

Prescriptive building and fire safety regulations specify explicit technical requirements—such as minimum fire resistance, compartmentation rules, travel distances, and exit widths—that must be complied with regardless of performance justification. These regulations form the backbone of national approval processes in most jurisdictions and are therefore a natural entry point for BIM-based automation. Early research identified automated code checking as one of the most commercially viable and institutionally acceptable applications of BIM, precisely because prescriptive rules are comparatively deterministic and rule-based (Poças Martins & Abrantes, 2010) [13].

3.5 National BIM-Based Prescriptive Checking Systems

Three countries have implemented BIM-enabled platforms specifically aimed at checking compliance against national prescriptive regulations, including fire safety provisions. All are partially automated providing decision support with human review retained (Singapore) [7], broad rule coverage but not end-to-end (Korea) [6] and fragmented deployment (US) [13].
Singapore has developed a mature nationwide workflow, streamlining the regulatory review. However, the rule coverage is not complete and is relying on specific schemas. The validation by experts has not been caried out which leaves the tool as a ad hoc tool, which will need a thorough analysis by fire safety engineers, before implementation.
In Korea the system has a strong alignment of national prescriptive rules with BIM checks and has carried out a large-scale implementation. However, the development is still partial and not complete. In the US some prescriptive clauses have been translated to computable logic. There is a limited nationwide uptake. Local code variations have not been accounted for. The different systems are shown in Tabel 1.

Tabel 1: Countries that have implemented BIM systems accounting for Fire Safety.

Country / Agency	Platform	Primary Scope (Prescriptive)	Fire-Safety Checks Highlighted	Data Input & Rules	Ref
Singapore	CORENET	Plan approval	Egress, sprinkler provision, compartmentation, general fire-safety requirements	BIM model submission and structured rule sets; authority-curated rule libraries	[7]
South Korea	SEUMTER	Bilding approval	Fire partitions, fireproofing, firewall regulations at site	BIM-based submissions mapped to codified rules	[6]
United States	SMARTcodes	Prescriptive checks	Compartmentations	Machine-readable rulesets mapped from code; BIM/IFC or native exports used ad hoc	[13]

3.6 BIM-Based Prescriptive Fire Safety Checking in Research

Beyond national platforms, research studies have addressed prescriptive fire safety checking within BIM environments, often as proof-of-concept implementations. Porto et al. (2018) [15] present the implementation of fire resistance and masonry rules (IT06 criteria) within the BIMSCIP system, demonstrating rule-based checking of structural fire resistance directly from BIM models. This type of work illustrates the technical feasibility of embedding national fire rules into BIM-based platforms but also reveals the reliance on case-specific rule interpretation and local code structuring.

Malagnino et al. (2022) [6] state that prescriptive checking dominates early BIM–FSE integration, particularly in contrast to performance-based fire engineering. Prescriptive rules are easier to encode because they map directly to geometric and material attributes already present in BIM models. As a result, most operational BIM–fire safety systems focus on verifying compliance rather than supporting risk-based design.

3.7 Limitations of Prescriptive BIM Approaches

Despite their relative maturity, BIM-based prescriptive checking systems face several structural limitations. First, national fire regulations are often written in natural language with implicit expert assumptions, making full formalization difficult. Second, BIM schemas—particularly IFC—lack dedicated fire safety structures, forcing prescriptive checks to rely on indirect attributes, naming conventions, or proprietary extensions (Siddiqui et al., 2021) [16].

Davidson and Gales (2021) [7] emphasize that prescriptive checks often require higher semantic resolution than is available in typical design models, such as explicit identification of

3.8 Position of Prescriptive BIM in Contemporary Fire Safety Practice

Current evidence indicates that BIM-enabled prescriptive regulation represents the most institutionally embedded application of BIM in fire safety, particularly within national approval and permitting systems. These systems have achieved a relatively high level of organisational and procedural maturity, enabling more consistent, transparent, and repeatable assessments of regulatory compliance.

At the same time, prescriptive BIM-based workflows are inherently oriented towards deterministic rule verification, reflecting their basis in codified legal requirements. As such, they primarily support compliance with explicitly defined criteria—such as minimum fire resistance, compartmentation, and egress provisions—rather than broader performance assessment or scenario-based evaluation.

Recent policy and research trends increasingly position prescriptive BIM checking as a foundational component within a broader digital fire safety ecosystem, rather than as a comprehensive solution in itself. Within this framing, prescriptive workflows provide a stable and legally anchored baseline upon which complementary performance-based, analytical, and life-cycle-oriented fire safety applications may be developed. Given their direct linkage to statutory approval processes, prescriptive BIM approaches are expected to remain a central—and often mandatory—element of digital fire safety governance in the foreseeable future (SFPE Foundation, 2024; Malagnino et al., 2022) [6], [18].

3.9 Advanced Technologies: Digital Twins, Artificial Intelligence, and Operational Fire Safety

Beyond design-stage applications, recent literature increasingly explores the role of digital technologies in supporting fire safety during the operational phase of buildings. The integration of BIM with digital twins (DT), Internet of Things (IoT) sensors, artificial intelligence (AI), and augmented or virtual reality technologies is proposed as a means to extend fire safety management beyond static compliance, enabling monitoring, decision support, and adaptive response throughout a building's use phase.

The SFPE Foundation (2024) highlights the growing interest in these approaches within professional practice, particularly in relation to emergency preparedness, incident response, and facilities management. Digital twins, in particular, are positioned as a mechanism for linking design intent, as-built conditions, and operational data within a unified information framework.

Almatared et al. (2024) [19] present a conceptual digital-twin framework for fire safety management during operation and facility management, integrating BIM, IoT, AI, and augmented reality technologies. Their work illustrates how such integrations may support enhanced situational awareness and more informed decision-making over time. Taken together, these contributions indicate that operational fire safety is increasingly recognised as a relevant domain for BIM-based fire safety engineering, extending the scope of digital fire safety beyond regulatory approval towards life-cycle application.

3.8 Validation, Practice, and Research Gaps

Case-based validation studies remain relatively rare, particularly those demonstrating complete pipelines from BIM to fire simulation and evacuation analysis. Akter et al. (2025) **Fejl! Henvisningskilde ikke fundet.** provide a notable example by applying an integrated BIM–FDS–Pathfinder workflow to a real high-rise building case, demonstrating qualitative plausibility and highlighting the applicability of such methods in resource-constrained contexts.

Across the literature, several persistent gaps emerge: limited interoperability using open standards, insufficient support for performance-based analysis within BIM schemas, poor integration of construction and operational phases into fire safety workflows, and a continued reliance on specialist, discipline-specific tools. These gaps indicate a clear need for approaches that strengthen data continuity, improve feedback between simulation and design, and support fire safety engineering across the full building life cycle.

Tabel 2: Comparison of Prescriptive BIM and Performance Based BIM in Fire Safety Regulation

Dimension	Prescriptive BIM	Performance-Based BIM
Regulatory principle	Compliance with explicitly defined, rule-based technical requirements (e.g. minimum fire resistance, exit length/widths, compartment sizes)	Compliance with functional or safety objectives reserach based and verified through analysis, simulation, and scenario evaluation
Primary BIM function	Automated or semi-automated code checking and decision support	Data integration platform linking BIM with fire, evacuation, and risk simulations
Typical BIM data requirements	Geometry, classification, basic attributes (fire rating, distances, areas)	High-LOD geometry, material properties, occupant data, scenario definitions
Common tools & workflows	Rule-based checkers, e-submission systems, proprietary schemas	BIM → CFD → evacuation models → result feedback to BIM
Interoperability characteristics	Often proprietary or schema-specific; limited IFC coverage	Strong reliance on native formats; IFC lacks dedicated FSE sub-models
Role of expert judgement	Supporting role (exception handling, interpretation of edge cases)	Central and indispensable (scenario definition, acceptance criteria)
Verification output	Pass / fail or non-compliance reports against codified rules	Quantitative performance metrics (ASET/RSET, FED, visibility, tenability)
Regulatory acceptance	High in jurisdictions with centralized approval systems	Accepted mainly as justification for deviations from prescriptive guidance
Scalability for authorities	High – enables consistent, repeatable checks across projects	Low – case-specific analysis limits standardization
Typical national examples	Singapore (CORENET), South Korea (SEUMTER), U.S. pilots (SMARTcodes)	Sweden (BBR analytical design), research-driven EU contexts
State of practice maturity	Institutionally mature, technologically bounded	Technologically advanced, institutionally constrained

4 State of the Art in Digital technologies

Digital technologies increasingly underpin the integration of fire safety engineering into BIM-based workflows, enabling more structured, data-driven, and traceable approaches to design, analysis, and regulatory compliance. These technologies support the translation of fire safety requirements and analytical methods into computable processes that can be applied across different project stages and disciplines.

Building on the BIM-focused discussion in Chapter 3, this chapter reviews the digital methods and tools that currently support fire safety engineering in both research and practice. It provides an overview of key technological domains—including compliance checking, simulation, artificial intelligence, and data interoperability—that form the technical foundation for contemporary and emerging BIM-based fire safety workflows.

4.1 Compliance checking

Fire safety compliance intersects with several technical disciplines that are already well established in BIM-based workflows, most notably energy design, structural engineering, and ventilation (HVAC/AVAC). In current practice, these disciplines primarily support prescriptive compliance through rule-based checks, while performance-based fire safety analysis remains largely dependent on external specialist tools.

Energy modelling workflows influence fire safety through design choices affecting compartmentation, façade construction, and air-tightness. From a prescriptive perspective, FireBIM use cases relate mainly to verifying fire compartments, material classifications, and boundary conditions derived from architectural and energy-driven building layouts. Performance-based considerations, such as smoke movement influenced by airtight envelopes, are typically addressed outside the BIM environment.

Structural engineering is closely linked to prescriptive fire safety through regulations governing fire resistance of load-bearing elements and structural separation. In FireBIM, this translates into rule-based verification of fire resistance ratings, compartment boundaries, and protected egress structures. Performance-based structural fire analysis, involving structural behaviour under fire exposure, remains weakly integrated with BIM and is mostly handled through specialised analysis tools.

Ventilation systems play a critical role in both prescriptive and performance-based fire safety. Prescriptive FireBIM use cases focus on verifying fire dampers, smoke compartments, and minimum smoke extraction provisions. Performance-based analysis of smoke control, tenability, and dynamic evacuation conditions relies on coupling BIM data with fire and evacuation simulations, with limited automated feedback into design models.

Overall, the state of the art shows strong disciplinary BIM support for prescriptive fire safety checks related to compartments, egress, and system presence, while performance-based fire safety integration remains fragmented. FireBIM addresses this gap by strengthening the consistency, traceability, and reuse of discipline-specific BIM data across both regulatory and analytical fire safety workflows.

4.1.1 Semantic and Data Quality Pre-checks (IDS, Completeness, Validity)

There are multiple software platforms and tools which focus on data quality (pre-check).

Solibri from Finland was early with their Model Checker software [19]. This is a custom 3D application, with a large and extensive set of routines for model analysis and data verification. They use their own technology and formats to model rules, which are included in the software, but configurable by knowledgeable users. They also provide a web-based tool *Solibri Checkpoint*, which they acquired from *Xinaps* in 2025 with a comparable but simplified scope.

Other applications exist, with various scopes: *DAQS.io* is a commercial platform to check data quality of Autodesk Revit datasets [20]. *Autodesk Navisworks* focuses more on planning and clash detection and provides limited model checking functionality. There are integration verification and validation tools inside common BIM-tools, but typically with limited scope and not related to Fire Safety.

Since 2024, due to the first release of the *Information Delivery Specification (IDS)* [21] by buildingSMART, multiple software vendors have incorporated support for this XML-based information requirement data format into their offerings. There are tools and interfaces for creating an IDS, such as the web-based IDS-editors from Solibri [22], *BIMcollab Nexus [23]*, *ACCA [24]*, *XBIM [25]* and *BIMvision [26]* and tools for validation of an IFC-dataset with such an IDS file, by the same companies, but also as software libraries by RDF.bg IDS Validator, ifcopenshell.org with *ifcteste [26]* and integrated into BIM authoring software (*Archicad [27]*, *BonsaiBIM [29]*, *BIMcollab Zoom*, *Bimvision [30]*, *IDS for Revit [31]*). Increasingly open-source implementations appear, often applying one of the software libraries mentioned before.

The BIMids [32]platform is a joint effort by Belgium and Luxembourg as a shared information requirement repository, aligned to IFC, but also mapped to common software. The requirements for various use cases are made available, and a fire safety use case will adopt the FireBIM project results. The platform also provides downloadable software templates and IDS-files.

D-studio, as partner in the FireBIM project, developed a series of routines to run data quality checks, as a combination of a data extraction plug-in and a PowerBI connector and template, which is applied with various construction projects and clients. The current implementation is based on Revit models, hosted locally or on the Autodesk Construction Cloud platform, but a first IFC/IDS-based implementation is also ongoing.

4.1.2 Automated Prescriptive Compliance Checks

CORENET [33] in Singapore presents an IFC-based building permit and compliance checking platform, with integrated and automated rule checking. This online platform ensures that every project passes through a rigorous and fast compliance checking procedure. CORENET X is already the third technological generation of the CORENET system. Similarly, Finland and Estonia also developed IFC-based building permit platforms, where a regulatory compliance check is (partially) automated, from uploaded IFC-models and back-end model checking services. In Finland, this is based on the Solibri system, whereas Estonia adopted the Dutch BIM.works system [35].

Bimpact [36] is a Revit plug-in based on the Dutch building regulations, but is more generic on area, daylight, ventilation. It works in real-time and references to the online regulation clauses.

CYPEFIRE [37] is a software suite for the validation of basic fire safety rules. There are tools for pressure and hydraulic systems, Fire Dynamics simulation and rule validation, which combines passive (compartmentalization, evacuation, external propagation, etc.) and active protection (extinguishers, detectors, etc.).

Bureau Veritas [39] from France develops the *ICHECK* plug-in for Revit which provides a series of automatic fire safety checks, including model feedback and generation of issues in the open BCF-format.

MBFire [40] is also a Revit add-in, to help with the design, documentation and calculation of sprinkler systems.

Tools such as BIMfire and FireBIM UK represent emerging BIM-based approaches to fire safety checking, primarily focused on supporting prescriptive requirements related to compartmentation, egress, and system presence within design models. These solutions typically function as decision-support tools integrated with BIM authoring environments, while their scope, standardisation level, and regulatory acceptance remain limited or context-specific.

The Solibri software, as already mentioned, provides model checking rules. They not only cover data quality, but there is a selection of design validation rules as well, including the extraction of compartments from models, egress routing, service penetration checks (through an extension [41]) and various generic configurable rules; e.g., the user may configure a property-check rule that checks the size of an *IfcSpace* or *IfcSpatialZone* (which could be used to model compartments), the width of a door, the length and slope of an *IfcRamp* or the Fire Rating of walls identified as compartment boundaries.

The *Building Safety Act 2022* in the UK [42] presents a regulatory competitor to FireBIM, particularly with its focus on digitalization and fire safety compliance. The Act mandates the creation of a Golden Thread, a digital record of critical safety information maintained throughout a building's lifecycle. This information must be easily accessible and updated to ensure that high-risk buildings meet fire and structural safety standards. The Act introduces strict Gateways during design and construction to ensure compliance before moving to the next stage. The Building Safety Regulator oversees the process, enforcing compliance with fire safety regulations. While the Building Safety Act is primarily focused on high-risk buildings and regulatory compliance post-construction, it overlaps with FireBIM's objective of integrating fire safety into the design phase. However, FireBIM's innovation lies in its early-stage integration with BIM models for fire safety, whereas the Building Safety Act focuses more on compliance throughout the lifecycle of high-risk buildings.

Various algorithms exist in literature and research on computational geometry to calculate the shortest path or escape route between a start and end point. These algorithms are typically 2D-based and are agnostic of the domain. There are algorithms based on weighted graph searching, such as Dijkstra's algorithm [56]or A* [57], which is an improved version. They are widely used in basis simulation or in computer games. The built-in escape path tool in Revit relies on an adjusted A*-based algorithm, although it cannot be configured by the user. Alternative methods are based on creating a visibility graph or search-area tessellation.

4.2 Digital Simulation

BuildingSMART has published a technical report on *occupancy movement analysis* in September 2025, on egress simulations and other types of crowd simulation [58]. This is beyond developed with the *Fire Safety & Occupant Movement* project by buildingSMART International, with the aim of developing dedicated *Model View Definitions (MVD)* for the IFC schema. However, this project or action has not led to published guidelines or technical standards so far.

Crowd:it [61]is a German crowd-simulation software, which can run a series of agents across a design, described from a CAD drawing in DXF-format, but it can also be integrated with *Vectorworks* as a plug-in.

VE is a suite of whole-building simulation tools, by IES. They provide the *Simulex* [62] module for occupant's movement analysis.

CSTB from France offers a series of fire safety simulation services [63],[64], including fire stability, evacuation, reaction to fire and smoke management, using a variety of custom software-tools.

We already mentioned *CYPEFIRE*, which also provides a *Fire Dynamics Simulator (FDS)* and related tools, with support for BIM-workflows via IFC.

There are various other CFD-based simulation systems and algorithms to simulate the behaviour and propagation of smoke, air and gasses, commercial, but also open source (e.g. *OpenFOAM [65]*).

Project partner Peutz (NL) has developed a range of specialised fire safety tools that support analytical fire safety engineering outside core BIM environments. Ontruimer focuses on egress and occupant evacuation analysis, enabling the assessment of evacuation times, crowd behaviour, and exit capacity under defined fire scenarios. Pintegraal addresses fire development and fire spread, supporting the evaluation of fire growth, compartment interaction, and exposure of building elements. These tools are typically used within performance-based fire safety workflows, relying on expert-defined scenarios and assumptions rather than deterministic rule checking. While data inputs can be derived from BIM models, the integration remains largely indirect, highlighting the need for improved interoperability and feedback loops—an issue directly addressed by the FireBIM project.

4.3 Artificial Intelligence and Machine Learning

The state of the art in this field has shifted from "computer-aided" (manual rule-checking using software like Solibri) to "AI-driven" Automated Compliance Checking (ACC). The cutting-edge research focuses on two main bottlenecks: (1) automating the digitization of regulations (converting text-based codes into computable rules) and (2) semantic enrichment of BIM models (ensuring the model understands "this is a fire door").

Research into Rule Interpretation is currently dominated by Natural Language Processing (NLP). The objective here is to automatically extract machine-readable rules from static building codes (such as NFPA, IBC, or Eurocodes). Standard deep learning architectures, specifically BERT (Bidirectional Encoder Representations from Transformers) and BiLSTM-CRF, are the industry standard for Named Entity Recognition (NER). These models are trained to identify specific entities (e.g., "sprinkler," "corridor") and quantitative constraints (e.g., "width > 1.2m"). More advanced studies utilize Semantic Role Labeling to parse the logic of complex conditional sentences, enabling the system to understand "if-then" dependencies inherent in fire safety regulations.

Once rules are extracted, the research focus shifts to Knowledge Graphs (KGs) and Ontologies as the bridge between regulatory data and the BIM model. Rather than checking rules directly against an IFC file, state-of-the-art methods convert both the BIM geometry and the regulatory rules into a unified graph format (using RDF/OWL standards). This approach allows for the use of Semantic Web Rule Language (SWRL) or SPARQL queries to perform the actual compliance checks. The major advantage of this method is its ability to handle "common sense" reasoning—for example, deducing that a glass partition functions as a wall for fire separation purposes, even if it is not explicitly labeled as such in the source file.

For existing buildings or retrofitting projects, Computer Vision and "Scan-to-BIM" technologies are the prevailing methods. Researchers employ deep learning architectures like PointNet++ or Graph Neural Networks (GNNs) to process 3D laser scan data. These models segment point clouds to classify safety-critical objects—such as detecting blocked fire exits or identifying the location of extinguishers—and update the BIM model to reflect the "As-Built" reality. Additionally, Convolutional Neural Networks (CNNs) like YOLO are frequently applied to site imagery to detect immediate hazards that standard BIM data might miss.

Regarding system architecture, the dominant framework in recent literature is a Hybrid Neuro-Symbolic approach. This architecture typically features three distinct components: a Parser that extracts geometry from Industry Foundation Classes (IFC) files; a Translator that uses NLP to parse text-based regulations; and a Solver that utilizes logic-based engines to perform the final check. This hybrid model combines the flexibility of neural networks (for understanding text and images) with the reliability of symbolic AI (logic rules), ensuring the system does not "hallucinate" a safety pass.

Looking toward the immediate future (2024–2025), the research is beginning to integrate Large Language Models (LLMs) and Graph Neural Networks (GNNs) more aggressively. Experimental frameworks are testing models like GPT-4 for "conversational compliance," where designers query the system directly about specific codes. However, these are currently tempered by the risk of hallucinations. Simultaneously, GNNs are being used to analyze the topology of buildings to predict smoke spread and evacuation bottlenecks, moving the field from static checking to dynamic risk prediction.

ndustry leaders prioritize tools that assist human experts rather than replace them, focusing on liability reduction, workflow efficiency, and the "human-in-the-loop" validation of safety-critical decisions.

In the domain of Regulatory Interpretation and Code Search, the industry has rapidly adopted Large Language Model (LLM) powered "Copilots." Platforms like UpCodes represent the cutting edge here. Instead of manual page-turning, designers use UpCodes Copilot to query vast regulatory databases conversationally (e.g., "What is the maximum travel distance for a Group B occupancy in Danemark?"). These tools utilize NLP to retrieve specific code sections, generate compliance checklists, and even perform basic calculations for occupant loads. Unlike the theoretical models in academia, these industrial tools are designed to "cite their sources," always linking the AI's answer back to the specific legal text to mitigate the risk of hallucination and ensure liability protection.

For Model Validation and Rule Checking, the usual approch remains deterministic rule-based engines, primarily Solibri, but these are evolving into hybrid AI systems. Solibri and cloud-native challengers like Verifi3D and CodeComply.ai are integrating machine learning to automate the tedious "classification" phase—automatically identifying that a specific geometry is a "fire wall" so that hard-coded safety rules can be applied to it. This hybrid approach—using AI to prepare the data and deterministic logic to check the data—solves the "Black Box" problem, ensuring that a fire safety pass/fail decision is always traceable and legally defensible.

The most visually advanced application of AI in industry is found in reality capture and site monitoring. Tools like OpenSpace and HoloBuilder utilize Computer Vision and "Visual Intelligence" to bridge the gap between the design (BIM) and the physical construction site. By analyzing 360-degree video footage or drone data, these platforms create a "Google Street View" of the job site. heir AI engines then automatically flag safety hazards—such as blocked fire exits, missing fire extinguishers, or exposed wiring—comparing the reality against the safety plan. This passive monitoring allows safety managers to identify compliance risks that traditional BIM checking might miss because they only exist in the physical world, not the digital model.

Finally, in the realm of Generative Design and Simulation, platforms like Hypar are moving compliance from a post-process check to a real-time design constraint. Instead of checking a completed design for fire safety errors, Hypar's generative algorithms can automatically generate stair layouts and corridor widths that already comply with egress calculations (e.g., minimizing travel distance). Similarly, while standard simulation tools like FDS (Fire Dynamics Simulator) and Pathfinder remain the industry heavyweights for smoke and evacuation modeling, they are increasingly being paired with AI-driven "Surrogate Models" that approximate complex physics in seconds rather than days, allowing engineers to test hundreds of fire scenarios rapidly during the early design phases.

This summary outlines the critical disconnects between current research and industrial application, along with the high-value opportunities emerging for 2025–2026.

4.4 Critical gaps

The single biggest barrier to adoption is legal liability. While academic models boast high accuracy (e.g., "95% precision in detecting fire hazards"), industry cannot accept a 5% error rate in life-safety applications. Current AI models often fail to explain why they flagged a design as compliant. This lack of explainable AI makes it impossible for an engineer to sign off on an AI's decision without re-doing the work manually. If an AI-approved building burns down, the legal framework for algorithmic negligence does not yet exist.

There is a fundamental disconnect between the pristine "Digital Twin" used in research and the messy reality of construction data. Academic papers often assume perfectly structured BIM models (IFC files) where every door is correctly labeled "Fire Door." Industrial data is often unstructured, with missing metadata or geometry that is merely "dumb lines." AI systems trained on prfect academic datasets often fail when deployed on fragmented, legacy, or incomplete real-world project files.

Current research is heavily skewed toward high-rise commercial buildings and general evacuation scenarios. There is a significant lack of specialized AI models for complex, high-risk facilities like hospitals, heritage buildings, or industrial plants where fire safety rules are far more nuanced. Furthermore, most systems focus solely on evacuation (getting people out) while neglecting suppression (sprinkler layout compliance) or structural fire resistance, leaving large portions of the fire safety strategy manual.

4.5 Opportunities

The next frontier is combining different types of AI (multimodal learning) to close the loop between design and construction. Instead of just reading text or just looking at 3D models, emerging systems will process site photos, 360° videos, and written reports simultaneously. An inspector could walk a site with augmented reality glasses that overlay the BIM fire strategy onto the physical room, using computer vision to instantly flag if a "1-hour fire wall" has been penetrated by unsealed pipes, verifying compliance in real-time.

We are moving from "compliance checking" (finding errors after they happen) to "generative compliance" (preventing errors before they occur). Rather than a passive tool that highlights a dead-end corridor in red, future tools will act as active design partners. They will automatically generate compliant floor plan options -optimizing stair locations and corridor widths to meet travel distance codes from the very first sketch, effectively "baking" safety into the geometry.

Opportunities exist to transition from static checks to dynamic monitoring. By integrating IoT sensors with the BIM Fire Model, a building's Digital Twin could evolve from a design archive into a live safety dashboard. In the event of a fire, such a system could calculate real-time safe evacuation routes based on actual smoke sensor data (rather than theoretical simulations) and guide first responders to the exact location of vulnerable occupants or hazardous materials.

4.6 Data Management and Interoperability

While BIM-authoring software is typically proprietary, most software can export and import datasets in the IFC-format (*Industry Foundation Classes*) [66]. As part of the schema, classes (or "entities") are declared in an inheritance hierarchy, from abstract and generic to more specific: from "root" (the mother of most entities) down to a wall, pump, slab or column. A subset of the schema also describes spatial entities (project, site, building, …), which has been used in the *BOT* ontology [67]. Alternatively, the whole IFC schema has been transformed into an ontology as *IfcOwl [68]* . While covering (most of) the IFC schema, it's not widely adopted, as it doesn't safeguard the user from the complexities of the IFC-schema. Throughout 2024 and 2025, we have witnessed the first hints of the *IFC5* schema, which is adopting more aspects of the LinkedData methodologies, with the IFC-schema behaving more like a classification system. However, software adoption is non-existent now, due to the speculative nature of this first iteration of the next generation of IFC. For FireBIM, the IFC4 schema remains the core reference, with *IFC 4.3* the currently published and ISO-standardised version.

Within the IFC-schema, some fire safety related concepts and properties have been defined, including objects to represent sprinklers, fire dampers, firehose reels and hydrants. Firerating is also a common property for many entities, but its value is left at the discretion of the user, to apply the local definitions and value conventions. Some specific fire safety property sets have been identified, such as *Pset_SpaceFireSafetyRequirements*, *Pset_DamperTypeFireDamper*, *Pset_FireSuppressionTerminalTypeFireHydrant* or *Pset_SensorTypeFireSensor*.

TU/Berlin has developed an ontology related to fire safety, called *FiSa [69]*, to enable classification of buildings and their components in the context of fire safety, combining building codes, regulations and guidelines. It is however, not referencing into legislation. It is mostly in English, but some German terms can be found as well. The building structure in this ontology is based on BOT, which is based on IFC.

Hypar [70] is a partially open-source toolkit, which connects with BIM models and generates conceptual designs using predefined rules. It automates early-stage design but focuses on zoning and performance criteria, not on verifying detailed fire safety regulations.

5 Industrial Applications and Use Cases

6 Research Gaps, Challenges, and Roadmap

Despite advances in compliance verification and digital simulation, several gaps remain in the integration of fire safety into BIM processes:

- Limited interoperability: Although standards such as IFC, IDS, and BCF exist, their adoption remains inconsistent. Proprietary tools (Revit, Solibri, etc.) offer partial functionality, often not aligned with local regulatory requirements.
- Lack of explicit rules: National regulations, such as the Belgian Royal Decree, do not always clearly define calculation methods (e.g., evacuation routes), which complicates the automation of checks.
- Lack of early integration: Fire safety is rarely integrated from the design phase onwards. Current solutions are implemented downstream, leading to costs and risks of non-compliance.
- Incomplete data and variable quality: BIM models suffer from semantic gaps and missing properties (e.g., FireRating, specific Pset), despite the emergence of IDS and ontologies such as BOT or FiSa.
- Underutilized simulation and AI: Simulation tools (FDS, Crowd:it, VE) and optimization algorithms (A*, Dijkstra) exist, but their integration into standardized BIM workflows remains in its infancy. AI could improve risk prediction, but limitations in interpretability and data quality are hindering its adoption.

Roadmap

1. Standardization and harmonization: Develop explicit sets of rules for fire safety, integrated into open formats (IFC, IDS) and adapted to national contexts.

2. Automation of checks: Create configurable rule engines for prescriptive compliance (compartmentalization, evacuation) and their integration into BIM platforms.

3. Early integration: Promote tools and workflows that enable the integration of fire safety from the design stage, in conjunction with collaborative platforms (e.g., BIMids).

4. Advanced interoperability: Strengthen ontologies (FiSa, BOT) and mappings between regulations and BIM models to ensure data consistency.

5. Simulation and AI: Develop hybrid solutions combining physical simulation (CFD, FDS) and AI to anticipate complex scenarios, while ensuring model transparency.

7 Conclusion

This State-of-the-Art (SotA) report establishes a common baseline of knowledge on fire safety engineering within BIM-based and digital workflows at the start of the FireBIM project. It documents the current regulatory, technological, and methodological landscape across research and industrial practice, providing a clear reference framework against which project results can be assessed.

By reviewing prescriptive and performance-based fire safety approaches, digital compliance checking, simulation methods, artificial intelligence, and interoperability standards, the SotA identifies existing capabilities as well as key limitations and gaps. This enables FireBIM developments to be positioned transparently relative to the current state of practice and supports consistent evaluation of technical progress across work packages. The SotA therefore serves as a stable reference for validation, comparison, and communication of project outcomes.

Recognising the rapid evolution of digital technologies, standards, and regulatory frameworks in the fire safety domain, the SotA will be treated as a living reference. A yearly review will be carried out to capture major developments such as new standards, regulatory changes, relevant research advances, and significant industrial implementations.

In parallel, continuous monitoring will take place throughout the project through participation in standardisation activities, collaboration with industry partners, and review of key scientific and professional publications. Relevant updates will be incorporated into subsequent FireBIM deliverables or referenced where appropriate, ensuring that the SotA remains an up-to-date and reliable baseline for the duration and impact of the project.

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