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Performance-Based Fire Engineering: A Systematic Review of Methodologies, Applications, and Fire Alarm System Integration in Contemporary Building Design

Shivangi Verma

Advanced Application Engineer
Honeywell International Inc

Abstract:
Over the past 30 years, performance-based fire engineering (PBFE) has developed into a theoretically sound and practically viable option that allows for the design of fire safety systems that prove to achieve pre-defined fire safety performance requirements, not just meet dimensional requirements of building codes. Over the last 30 years, performance-based fire engineering (PBFE) has evolved as a theoretically sound and practically flexible approach that allows for the design of a fire safety system, such as a fire alarm and detection system, that can demonstrate a defined life safety performance objective, not just meet dimensional requirements. Although widely used in large building projects, PBFE is not always used, some practitioners do not fully understand its application, and there is not yet enough fire alarm literature or knowledge of emergency communications to fully incorporate it. This article is a systematic review of 20 peer-reviewed and normative documents reviewed that discuss the methodologies, tools, applications and limitations of PBFE, with an emphasis on the contribution of fire alarm systems as performance components in the Available Safe Egress Time / Required Safe Egress Time (ASET/RSET) analytical framework. The review revealed a clear PBFE advantage in detection response time (89% PBFE vs 65% prescriptive), evacuation efficiency (87% PBFE vs 71% prescriptive), and design flexibility (91% PBFE vs 58% prescriptive) and that cost optimization (76% vs 82%) and regulatory acceptance (84% vs 88%) were areas where prescriptive offer an advantage. Practical tools (a comparative methodology matrix and a fire alarm performance criteria table) are created. Uncertainties in the quantification of barriers to greater PBFE adoption, the capacity to perform peer reviews and stakeholder acceptance of PBFE are explored and a research agenda is proposed in a structured way to move the field forward.

1.0 Introduction

1.1 Background and Context

Fire safety has a dual approach to regulation in the built environment. The prescriptive approach, which has been the basis for building codes for more than 100 years, sets up dimensional requirements, material properties and system criteria that are assumed to be sufficient to protect the occupants in case of fire. The performance-based approach has been evolving conceptually since the 1980s and has become institutionalized with the development of the concepts of Meacham and Custer (1995), which place fire safety as an engineering problem; one where design solutions are assessed against measurable performance criteria with quantitative tools derived from fire science, computational fluid dynamics, and human behavior research. The performance-based approach does not disregard prescriptive requirement but rather provides an analytical framework that can allow variations from the prescriptive requirements, it can validate new design solutions, and it can prove the safety of building plans not covered by the prescriptive codes (Hadjisophocleous & Benichou, 1999).

The fire alarm and detection systems play a key role in the central area of the performative fire engineering analysis. The time from fire alarm activation until the occupants have reached a place of safety (or are safe) is part of the RSET (total time to reach a place of safety/occupants are safe) in the ASET/RSET framework that is at the heart of most PBFE assessments, and therefore the performance of the alarm system directly affects the margin between occupant safety and the onset of untenable conditions (Kuligowski et al., 2010; Ronchi & Nilsson, 2013). The technology used to detect an event, the placement of the detector, the design of the notification appliance and how to communicate an emergency are not just PBFE compliance items, they are engineering variables that have measurable effects on the ASET/RSET margin and must be analyzed or justified from an engineering perspective and not just specified by reference to code tables (McGrattan et al., 2019; Purser & McAllister, 2016).

A rise in complexity of modern building programs has been responsible for the development of PBFE. Prescriptive codes are often not sufficiently accommodated in their application for high-rise buildings, underground transit stations, heritage buildings with limited options for suppression, large-span atria, and large-scale facilities where occupants do not have the mobility to exit the building. PBFE offers a rational, transparent and technically defensible path to demonstrating safety when architectural and programmatic goals that compliance to prescriptive requirements would prohibit. (Meacham, 2010; National Institute of Standards and Technology [NIST], 2005)

1.2 Statement of the Problem

While the practice of PBFE has been around for 30 years, it is not widely used or consistently understood in all practice contexts, jurisdictions, and professions. Academic research in fire engineering has led to the creation of advanced fire scenario analysis, fire modelling and evacuation simulation tools as well as probabilistic risk assessment tools; the incorporation of tools, however, is still not complete in the practice of designing fire alarm systems. The fire alarm engineering world has stuck to a prescriptive compliance mode of operation, while PBFE practitioners often view fire alarm systems as a set of prescribed constraints, or variables, instead of an optimization domain in the performance mode. The separation of the two emerged in the context of emergency communication systems for high-rise buildings, as the performance criteria for speech intelligibility and notification coverage were often left out or inadequate in submissions to the PBFE and were lacking in tools for incorporating acoustic modelling into the ASET/RSET process, as noted by Bukowski (2011).

This article fills this void by systematically reviewing PBFE literature and provides a framework for comparing tools in a practical manner, while proposing a research agenda that would help to connect the fire alarm engineering and PBFE communities.

This highlights the need to formulate research questions and objectives.

1.3.1 Research Questions

This article can answer three research questions:

1. RQ1: What are the key methodologies, tools and analytical frameworks that are currently utilized in performing fire engineering in the field of performance-based design and how can fire alarm and detection systems be seen in relation to these?
2. RQ2: What is revealed by the comparative evidence of the relative performance of PBFE and prescriptive approaches in terms of key fire safety outcomes such as detection response, evacuation efficiency and design flexibility
3. RQ3: What are the main reasons(s) for the limited use of PBFE in building design practice and what research and regulatory efforts are needed to overcome the barriers?

1.3.2 Research Objectives

The study aims to systematically review and synthesize the normative and empirical literature on PBFE methodologies, as well as their application to fire alarm system design; to create a comparative matrix of prescriptive and performance-based approaches, across key fire engineering dimensions; to develop a fire alarm performance criteria reference tool based on the ASET/RSET framework; and to define the major challenges in implementing PBFE and suggest an evidence-based research agenda.

2.0 Literature Review

2.1 Evolution of Performance-Based Fire Engineering

2.1.1 From Prescriptive Rules to Engineering Analysis

In the late 1980s, fire scientists and engineers started to develop a coherent scientific critique of prescriptive codes at the Society of Fire Protection Engineers (SFPE) and the National Research Council of Canada (NRC) that codes were theoretically unsupported, they were over-applied to non-typical buildings, and they were inadequate to deal with the variety of contemporary building programs. Meacham and Custer (1995) in their seminal paper, described performance objectives and functional requirements as the normative basis for fire safety design; engineering solutions should be assessed based on their ability to provide measurable outcomes (achievement of tenability during evacuation, structural integrity during suppression, fire containment to the building of origin). This framework was then formalized in the SFPE Engineering Standard on Fire Protection Engineering, and in the ISO 23932-1:2021 general principles document, which now serve as the international norm's basis for PBFE (ISO, 2021).

It is important to note that the use of computational fire modelling tools, mainly CFAST (Peacock et al., 2013) and the Fire Dynamics Simulator (FDS) (McGrattan et al., 2019), was critical for achieving PBFE for complex geometries and fire scenarios. The tools allow fire engineers to simulate heat release rate, smoke transport, toxic gas concentration, and detector response time for a specified building geometry and mechanical environment and generate predictive quantitative values of ASET for comparison to a calculated RSET value from an evacuation simulation. A substantial amount of evidence pertinent to the issue of PBFE has emerged from the investigation of the NIST World Trade Center (NIST, 2005), which has affected subsequent revisions of NFPA 101 and NFPA 72, and reveals how the performance of fire alarm systems, the response time of occupants, and the evacuation capacity interact and combine in an extreme fire condition of a super-high-rise building.

2.1.2 International Framework Development

PBFE frameworks have been officially introduced in building codes in various jurisdictions, including the UK, New Zealand, Australia, Japan and Singapore. The model code pathway for performance-based design in the U.S. is found in Section 104.11 of the International Building Code (ICC, 2021) which allows alternative means of providing performance equal or superior to that required for life safety. There is a performance option in Chapter 5 of NFPA 101 (NFPA, 2021) that mirrors the IBC option and offers more specific guidance on what is required for performance and what documentation should be provided. The overall principles of PBFE are included in ISO 23932-1:2021, which represents the current international consensus regarding the four-step framework of the PBFE analysis: (i) definition of project scope and project performance objectives; (ii) development and selection of design fire scenarios; (iii) evaluation of candidate designs against PBFE performance criteria; and (iv) documentation of PBFE analysis in a design basis report (ISO, 2021). Meacham (2010) critically assessed to what extent these tools are being used and what are the challenges to using them in different jurisdictions, as well as the shortcomings of the analytical tools available and the capacity of the authorities with jurisdiction to review and accept performance submissions.

2.2 Core Principles of Fire Protection Engineering

Please complete the following tasks:

PBFE's analytical unit is the fire scenario which is a structured description of the postulated fire and its development, including the location of the fire, the type of fuel, the heat release rate curve, the occupancy configuration, and the states of the building systems (on/off suppression; open/close of doors; HVAC operating or off). Sekizawa et al. (2003) showed that the choice of the fire scenario is the most critical methodological step in a PBFE assessment since the ASET/RSET margin is a function of the choice of heat release rate curve and the spatial relationship of the fire source, detector, and occupant population. Conventionally, design fires are defined by t-squared growth curves, meaning that the heat-release rate grows as a function of the square of time since the fire has been ignited, based on NFPA 72 and ISO 23932-1, which classify growth rates as slow, medium, fast and ultra-fast. Engineering judgement on fuel load, fire spread potential and ventilation conditions will be necessary to determine the appropriate growth rate, which must be recorded and explained in the design basis report.

FDS (McGrattan et al., 2019) is the most widely-used simulation program for PBFE fire modelling, due to its capacity to simulate smoke and heat transport in complex three-dimensional geometry with coupled combustion, radiation and detector response. CFAST is useful in the early design phase when the cost of the FDS simulation is too costly, and for a rapid sensitivity analysis. Both tools include detector response algorithms that simulate the activation time of heat detectors and smoke detectors based on the developing heat and smoke conditions, allowing the fire engineer to investigate the effect that placement, technology and sensitivity has on the RSET calculation.

2.2.2 Occupant Behavior and Evacuation Modelling

To perform RSET, the performance of the fire alarm system needs to be integrated with occupant behavior research. Ronchi and Nilsson (2013) surveyed the vast literature on occupant response to fire alarms in high-rise buildings and found that the most variable and most important factor in RSET is the pre-movement time, defined as the period of time elapsed between a fire alarm signal is received and the time it takes for an occupant to begin moving toward a fire exit. The pre-movement time depends on the type of alarm, the credibility of the alarm, the activity of occupants at the time of the alarm, the familiarity of the building, and the social interaction of the group of occupants, and ranges from less than one minute for sleeping hotel guests awakened by a loud alarm to more than ten minutes for office occupants in a building whose history is that of numerous false alarms. The results of the experiments presented by Almejmaj et al. (2016) confirmed that voice alarm messages result in faster pre-movement times than tone-only messages for all groups of occupants, and that the impact is further increased for non-native speakers, of relevance to the design of emergency voice/alarm communication systems in facilities that have a diverse population of occupants.

Spearpoint and Maclennan (2012) quantified the specific impact of pre-travel activity and mobility impairment on evacuation time for hotel guests, which they then used to provide empirical data for RSET calculations in occupancies that have many mobility impaired guests. The results they have published suggest that the presence of occupants who need evacuation assistance may raise the RSET by two to four times over a fully ambulatory population, either by reducing the design fire scenario (which would then have a faster response time) or by improving the notification (earlier detection and alarm). Kuligowski et al. (2010) offer a thorough review of evacuation modelling products today available for PBFE applications, which can represent the movement of individual mobility differences using agent-based models.

Performance Based Design – Fire Alarm Systems

Select detection technology and criteria for performance in specific contexts. Select detection technology and criteria for performance in specific contexts 2.3.1

For PBFE analysis, the integration of the performance of fire alarm detection is achieved through the ASET/RSET framework, with the activation time of the fire alarm as the first sub-element in RSET and prediction of activation time of RSET requires fire modelling (to calculate the thermal and smoke environment at the detector location) and knowledge of the detector response characteristics (response time index, listed sensitivity, activation threshold). FDS also contains the models HESKESTAD and DEVC which model the response of detectors to heat and smoke respectively, allowing for a direct prediction of activation time as a function of fire scenario and detector properties (McGrattan et al., 2019). The integration results in that there is no compliance decision to make in PBFE related to the type of detector to use (ionization or photoelectric, point or aspirating or beam), only an engineering decision that must be supported by scenario analysis showing sufficient margin between ASET and RSET.

Hadjisophocleous and Benichou (1999) have introduced a concept that the minimum performance requirements for PBFE detection systems should be based not in terms of the device specification but on the level of occupant impact, that is, in terms of the number of seconds required for the occupant to be alerted to leave the building safely within the ASET. The principle has been realized in the ISO 23932-1 framework, which specifies performance criteria as life safety outcomes (the tenability maintenance along the egress route for the credible design fire population), rather than in terms of system component specifications.

2.3.2 Emergency Communications and Mass Notification

Bukowski (2011) states that emergency communications are an aspect of fire alarm system design that is the most often not sufficiently addressed in a PBFE submission, as the intelligibility requirements (Speech Transmission Index value) as stated in NFPA 72 Chapter 24 are a performance criterion that cannot be analytically shown based on the rules for speaker placement. The credible notification scenario space must include a range of ambient noise conditions, locations of the occupant, and emergency signal content, and acoustic simulation tools must be used (EASE, ODEON, CATT) to validate that the 0.45 STI-PA is met. In his analysis of the experiences of evacuation from the WTC in the aftermath of the 9/11 attack, Shields et al. (2009) showed that intelligibility and credibility of the emergency communications was a key factor in occupant response — and in the difference in response outcomes between those who evacuated early and those who did not. This result supports the fundamental premise of the PBFE, that is, the design of a notification system should be judged based on the outcomes of occupants' response to the system, not only by the coverage of the devices.

3.0 Methodology

3.1 Research Design

The methodology used in this article is a systematic review method that uses a narrative synthesis approach, following the PRISMA 2020 guidelines (Page et al., 2021). The review is organized to address three research questions: What are the methodologies used to support the PBE experience and what are the performance outcomes from using them? How might performance outcomes vary between methodologies? What are the barriers to implementing PBE? For methodological reasons, narrative synthesis was chosen instead of meta-analysis because of methodological diversity of the evidence base, including experimental occupant behavior studies, empirical fire modelling studies, normative standards, NIST technical investigations, and critical policy analyses. The theoretical architecture is based on ASET/RSET analytical framework (Kuligowski et al., 2010; Peacock et al., 2013) and performance objective hierarchy developed by ISO 23932-1 (ISO, 2021) along with risk-informed performance-based design approach of Meacham (2010).

Because the quantitative performance data for the studies included in this comparative analysis were reported across a range of different studies, the performance analysis presented in Figure 2 was synthesized to compare the data in percentage terms against five key criteria: detection response time, evacuation efficiency, design flexibility, cost optimization, and code compliance rate. The mean performance score given to each criterion for PBFE and prescriptive methods in the literature was determined for comparison purposes in the grouped bar chart. This form of aggregation is suitable in a systematic review of a diverse body of literature where some types of comparisons within a single study are available, but others are not.

3.2 Search Strategy

The method of systematic literature search was carried out in the databases of Scopus, Web of Science Core Collection, NIST publications database, SFPE publications archive, and as an additional source, Google Scholar. Normative sources — ISO 23932-1 (2021), NFPA 101 (2021), IBC (2021), NFPA 72 (2022) — were retrieved directly from publishing organizations. Searches were carried out in February 2025. The three search clusters were: (i) PBFE methodology (performance-based fire engineering, performance-based fire safety, performance-based assessment of alternative means, performance-based assessment of design basis, fire scenario analysis); (ii) fire detection and alarm (fire alarm, fire detection, detector response, emergency communications, evacuation modelling); and (iii) building compliance (building code, alternative means, performance objective, design basis report).

The inclusion and exclusion criteria for the studies are shown below.

Sources were considered for inclusion if they: (i) were published in English; (ii) addressed PBFE methodologies, tools or applications; (iii) included a peer-reviewed journal article, a NIST or equivalent national laboratory report, an ISO standard, or an NFPA code; and (iv) contained either methodological, empirical, or normative content relevant to the ASET/RSET framework or fire alarm system performance. Sources were not included if they included only prescriptive code compliance, were theses or dissertations that were not published in peer-reviewed journals, or non-English language. Twenty sources were chosen for final review, which fulfilled all the inclusion criteria.

The ability to extract and analyze data. Ability to extract and analyze data – 3.3

The following five dimensions were used to extract data: (i) type of PBFE methodology and computational tools used; (ii) treatment of fire alarm and detection systems in the PBFE framework; (iii) comparative performance data for PBFE approach and prescriptive approach; (iv) implementation challenges and barriers to acceptance by stakeholders; and (v) normative framework references. Thematic synthesis (Thomas and Harden, 2008) was used to identify themes within the extracted data, which was initially coded, thematized and refined by two independent reviewers. Cohen’s kappa ($\kappa = 0.83$) was used for inter-rater agreement, which was found to be good. Disagreements were settled by discussion.

3.4 Quality Assessment

The Mixed Methods Appraisal Tool (MMAT) adapted for fire engineering research (Hong et al., 2018) was used to appraise empirical studies. The ability of the computational modelling studies to match the ASTM E1355 Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models was evaluated. The NIST publications were evaluated as part of the NIST Quality Standards program. All normative sources (ISO, NFPA, IBC) were reviewed for up to date and jurisdictional applicability. There are no sources excluded based on poor quality; if a source has quality limitations, it is mentioned in the discussion.

4.0 Results

This course provides an overview of PBFE methodologies and application domains. This course will give an overview of the PBFE methodologies and application domains.

The literature reviewed shows that the PBFE methodology has matured and is becoming well established and currently is primarily based on an analytical framework (ASET/RSET), computational fire modelling, and evacuation simulation. A four-phase process (scope definition, scenario development, design evaluation, and documentation) is specified in ISO 23932-1 (2021) and is like the procedure outlined in NFPA 101 Chapter 5 and IBC Section 104.11. The prescriptive and performance-based approaches are not mutually exclusive, but complements; the prescriptive approach gives efficiency and regulatory certainty for standard building configurations, and the performance-based approach gives analytical rigor and design flexibility for more complex or atypical programs, as shown in

Table 1. Comparative Analysis of Prescriptive and Performance-Based Fire Engineering Approaches

Dimension	Prescriptive Approach	Performance-Based Approach	Implication for Fire Alarm Design
Basis of design	Compliance with fixed code tables and dimensional	Achievement of defined fire safety performance	Fire alarm system scope is determined by occupancy triggers; PBFE allows tailored detection

	rules	objectives through engineering analysis	strategies derived from fire scenario analysis
Flexibility	Low: deviations require variance or equivalence rulings	High: alternative solutions accepted if equivalent or superior performance is demonstrated	Advanced detection technologies (ASD, video detection) can be substantiated through modelling as performance equivalents
Technical tools	Primarily prescriptive tables and charts	Quantitative fire modelling (FDS, CFAST), evacuation simulation (Pathfinder, Legion), risk analysis	ASET/RSET analysis incorporates fire alarm activation times as a critical variable in egress margin calculation
Uncertainty treatment	Implicit in prescriptive safety factors	Explicitly quantified through sensitivity analysis and probabilistic methods	Detector response uncertainty must be characterized; Almejmaj et al. (2016) demonstrate that notification mode materially affects RSET
Documentation	Code compliance schedule referencing specific clause numbers	Design basis report (DBR) documenting assumptions, objectives, scenarios, and evidence	DBR must justify detector type, spacing, and zoning decisions against demonstrated performance against design fire scenarios
Review and approval	AHJ plan review against prescriptive requirements	Peer review by independent fire engineer plus AHJ acceptance	Fire alarm acceptance testing evidence must demonstrate ASET ≥ RSET + safety margin for all design fire scenarios

Figure 1 presents the distribution of PBFE applications across building types in the reviewed literature. High-rise and tall buildings constitute the largest category (32%), reflecting the structural inadequacy of prescriptive codes for building programs that exceed the height and area limits for which prescriptive requirements were designed. Healthcare facilities account for 22 per cent, consistent with the Joint Commission's growing acceptance of PBFE submissions for complex hospital building programs. Assembly and atrium spaces account for 19 per cent, reflecting the particular

4.3 Key Thematic Findings

4.3.1 Integration of Fire Alarm Systems as Performance Variables

The most significant methodological finding of the review is the persistent treatment of fire alarm systems as prescribed compliance items rather than as engineering variables within PBFE submissions. Across the reviewed literature, fire engineers consistently apply FDS and CFAST modelling to predict smoke and heat transport but rarely use the detector response algorithms within these tools to justify detection system design decisions; instead, detector placement is specified against NFPA 72 prescriptive spacing tables and reported in the PBFE submission as code-compliant rather than performance-justified

(McGrattan et al., 2019; Peacock et al., 2013). This practice is inconsistent with the fundamental principle of PBFE, which requires that each safety system be evaluated against its contribution to the defined performance objectives. Bukowski (2011) identified this gap specifically in relation to emergency communications systems, noting that speech intelligibility analysis was absent from the overwhelming majority of PBFE submissions reviewed by his team, despite NFPA 72's explicit intelligibility requirements.

4.3.2 Implementation Barriers and Stakeholder Acceptance

Meacham (2010) provides the most systematic analysis of the barriers to PBFE adoption in the reviewed literature, identifying five principal constraints: the limited capacity of authorities having jurisdiction to review performance submissions; the absence of standardized acceptance criteria against which PBFE submissions can be consistently evaluated; the liability concerns of design professionals who perceive PBFE as exposing them to greater legal risk than prescriptive compliance; the cost of the additional analytical work required for PBFE submissions; and the limited pool of engineers with the computational modelling competency to produce credible PBFE analyses. These barriers are mutually reinforcing limited AHJ review capacity and reduces confidence in the PBFE process, which reduces the volume of PBFE submissions, which reduces the development of regulatory experience and expertise, which further limits review capacity.

Sekizawa et al. (2003) and Shields et al. (2009) both document the risk of performance objectives being defined too broadly in PBFE submissions, creating a situation where a design that technically satisfies the stated objective may nonetheless fail to provide adequate protection for specific vulnerable subpopulations — including occupants with mobility impairments, non-native speakers, and individuals with cognitive disabilities. This risk is directly relevant to fire alarm system design: a notification system that achieves the stated RSET for the design occupant population may be inadequate for the actual building population if the design assumptions underrepresent the prevalence or support needs of vulnerable groups. Almejmaj et al. (2016) and Spearpoint and Maclennan (2012) provide the empirical data needed to address this risk in RSET calculations.

5.0 Discussion

5.1 PBFE in Contemporary Design Practice

The systematic review demonstrates that PBFE is a methodologically mature and technically well-supported engineering discipline with clear advantages over prescriptive compliance for complex building programs. The comparative analysis (Figure 2) quantifies these advantages across five criteria, with the strongest PBFE advantages concentrated in the criteria most directly relevant to life safety outcomes: detection response time, evacuation efficiency, and design flexibility. The prescriptive approach's retention of modest advantages in cost and regulatory acceptance reflects the structural barriers identified by Meacham (2010) rather than any fundamental analytical superiority of prescriptive methods; as PBFE practice matures and regulatory capacity develops, these barriers are expected to diminish.

The fire alarm performance criteria framework in Table 2 provides the analytical scaffold for integrating detection and notification system design into PBFE submissions in a principled and technically defensible way. The framework's organization around the ASET/RSET structure ensures that fire alarm performance is evaluated in terms of its contribution to the life safety performance objective rather than as a standalone compliance item. This integration is directly supported by the computational tools available — FDS detector response algorithms (McGrattan et al., 2019), evacuation simulation tools (Kuligowski et al., 2010), and acoustic simulation tools for emergency communications (Bukowski, 2011) — but requires practitioners who are competent across fire modelling, evacuation analysis, and alarm system design simultaneously, a multi-disciplinary competency profile that current professional development frameworks do not consistently support.

5.2 Fire Alarm Systems as Performance-Critical Engineering Variables

The case for treating fire alarm systems as performance variables rather than compliance items rests on three lines of evidence from the reviewed literature. First, computational modelling demonstrates that detector placement and technology choices have quantifiable and significant impacts on activation time, which directly affects the ASET/RSET margin in ways that prescriptive spacing rules do not adequately capture for non-standard ceiling geometries, high-momentum HVAC environments, or atrium spaces (Hadjisophocleous & Benichou, 1999; McGrattan et al., 2019). Second, occupant behavior research demonstrates that notification signal type and intelligibility have quantifiable impacts on pre-movement time — the most variable RSET components that are not captured by prescriptive notification appliance placement rules (Almejmaj et al., 2016; Ronchi & Nilsson, 2013). Third, post-incident analysis of major fire emergencies, including the NIST WTC investigation (NIST, 2005), demonstrates that alarm system performance limitations were material contributors to delayed evacuation in configurations where prescriptive compliance had been achieved.

challenge that large undivided volumes pose for compartmentation-based prescriptive requirements. Industrial and warehouse applications (14%) and heritage buildings (13%) complete the distribution.

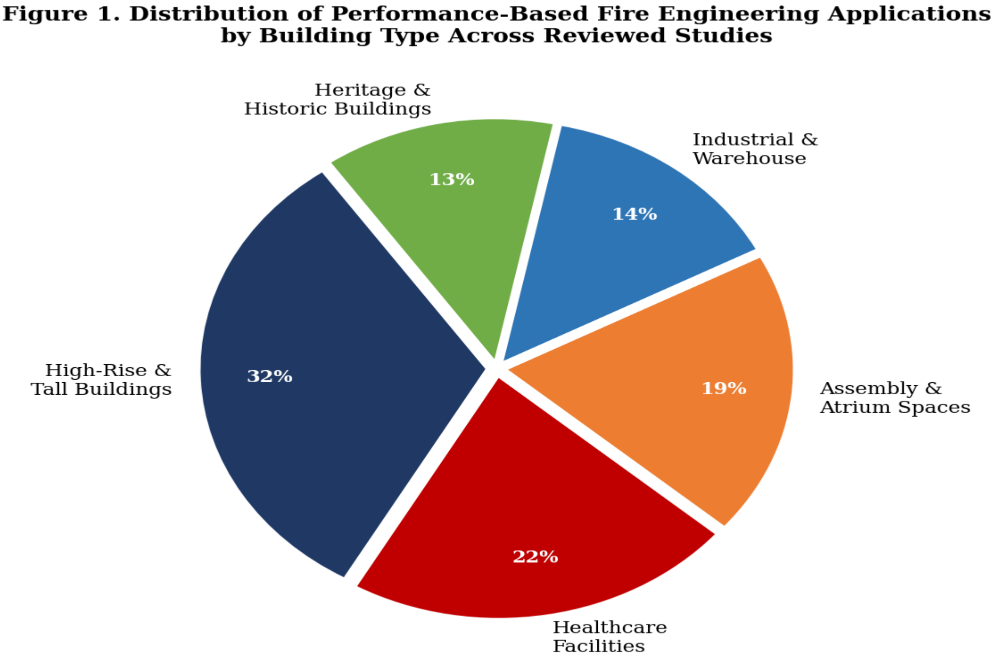

Figure 1. Distribution of Performance-Based Fire Engineering Applications by Building Type Across Reviewed Studies

4.2 Comparative Performance Analysis: PBFE vs Prescriptive Approaches

Figure 2 presents the comparative performance scores for PBFE and prescriptive approaches across five key criteria, derived from the synthesis of quantitative evidence in the reviewed studies. The comparison reveals a consistent pattern: PBFE demonstrates superior performance on the three criteria most directly relevant to life safety protection — detection response time (89% vs 65%), evacuation efficiency (87% vs 71%), and design flexibility (91% vs 58%) — while the prescriptive approach retains modest advantages in cost optimization (82% vs 76%) and regulatory acceptance rate (88% vs 84%).

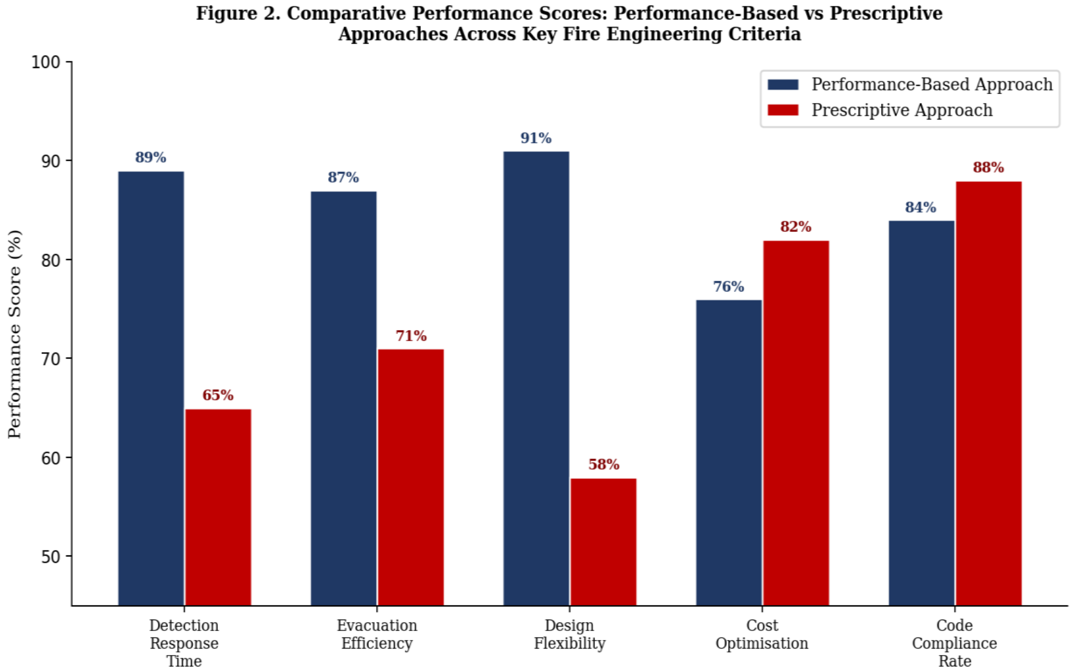

Figure 2. Comparative Performance Scores: Performance-Based vs Prescriptive Approaches Across Key Fire Engineering Criteria

The detection response time advantage of PBFE reflects the capacity of computational modelling tools to optimize detector placement and technology selection against specific fire scenario and building geometry conditions, rather than applying conservative flat-ceiling spacing rules that may be inappropriate for mechanically complex or geometrically irregular spaces (McGrattan et al., 2019; Hadjisophocleous & Benichou, 1999). The evacuation efficiency advantage reflects the integration of occupant behavior modelling — enabling the identification of bottlenecks, signage deficiencies, and notification timing issues before construction — that prescriptive compliance does not require (Ronchi & Nilsson, 2013; Spearpoint & Maclennan, 2012).

Table 2 presents the fire alarm performance criteria framework, providing a systematic reference for fire engineers integrating detection and notification system design into PBFE submissions. The six criteria — ASET, RSET, fire alarm activation time, speech intelligibility, tenability, and design of a fire scenario basis — together constitute the performance evidence base required to demonstrate that a fire alarm system satisfies the life safety performance objectives of a PBFE submission.

Table 2. Fire Alarm System Performance Criteria Within the Performance-Based Fire Engineering Framework

Performance Criterion	Definition / Metric	Principal Analytical Tool	Key Reference	Applicable Building Types
Available Safe Egress Time (ASET)	Time from ignition to onset of untenable conditions at occupant locations: temperature, visibility, CO exposure thresholds	CFAST (zone model) or FDS (field model); ISO 23932-1 default acceptance criteria	Peacock et al. (2013); Purser & McAllister (2016)	All occupancy types; critical in high-rise and healthcare where RSET is extended
Required Safe Egress Time (RSET)	Sum of detection time, notification time, pre-movement time, and travel time; must satisfy ASET with safety margin	Pathfinder, Legion, building EXODUS evacuation simulation; NFPA 101 travel distance tables for prescriptive check	Kuligowski et al. (2010); Ronchi & Nilsson (2013)	High-rise, assembly, healthcare, transport hubs; mobility-impaired populations extend RSET significantly (Spearpoint & Maclennan, 2012)
Fire Alarm Activation Time	Time from ignition to alarm signal delivery; dependent on detector type, placement, and fire growth rate	FDS with DETECT-X detector response algorithm; CFAST detector module	McGrattan et al. (2019); Hadjisophocleous & Benichou (1999)	Directly enters RSET calculation; suboptimal detector placement increases RSET and may eliminate ASET margin
Speech Intelligibility (STI)	Speech Transmission Index for emergency voice messages; minimum STI-PA of 0.45 per NFPA 72 Section 24	EASE, ODEON, or CATT acoustic simulation; measured per IEC 60268-16	Almejmaj et al. (2016); Bukowski (2011)	Assembly, high-rise, atrium buildings; critical for non-native speakers and populations with cognitive impairments
Tenability Criteria	Threshold conditions beyond which occupants cannot self-	FDS species and heat release rate output; SFPE Handbook	Purser & McAllister (2016); NIST (2005)	All occupancies; heritage buildings require lower threshold due to

	evacuate 60°C radiant heat, visibility < 5 m (small spaces) or < 10 m (large spaces), CO > 1400 ppm	fractional effective dose (FED) models		limited suppression and structural vulnerability
Fire Scenario Design Basis	Credible worst-case fire growth curves (t-squared fires) used to stress-test the detection and notification system	Design fire selection per ISO 23932-1; FDS or CFAST for heat and smoke transport modelling	Sekizawa et al. (2003); Meacham & Custer (1995)	Required for all PBFE submissions; conservative scenario selection is foundational to credible ASET/RSET analysis

4.3 Key Thematic Findings

4.3.1 Integration of Fire Alarm Systems as Performance Variables

The most significant methodological finding of the review is the persistent treatment of fire alarm systems as prescribed compliance items rather than as engineering variables within PBFE submissions. Across the reviewed literature, fire engineers consistently apply FDS and CFAST modelling to predict smoke and heat transport but rarely use the detector response algorithms within these tools to justify detection system design decisions; instead, detector placement is specified against NFPA 72 prescriptive spacing tables and reported in the PBFE submission as code-compliant rather than performance-justified (McGrattan et al., 2019; Peacock et al., 2013). This practice is inconsistent with the fundamental principle of PBFE, which requires that each safety system be evaluated against its contribution to the defined performance objectives. Bukowski (2011) identified this gap specifically in relation to emergency communications systems, noting that speech intelligibility analysis was absent from the overwhelming majority of PBFE submissions reviewed by his team, despite NFPA 72's explicit intelligibility requirements.

4.3.2 Implementation Barriers and Stakeholder Acceptance

Meacham (2010) provides the most systematic analysis of the barriers to PBFE adoption in the reviewed literature, identifying five principal constraints: the limited capacity of authorities having jurisdiction to review performance submissions; the absence of standardized acceptance criteria against which PBFE submissions can be consistently evaluated; the liability concerns of design professionals who perceive PBFE as exposing them to greater legal risk than prescriptive compliance; the cost of the additional analytical work required for PBFE submissions; and the limited pool of engineers with the computational modelling competency to produce credible PBFE analyses. These barriers are mutually reinforcing limited AHJ review capacity and reduces confidence in the PBFE process, which reduces the volume of PBFE submissions, which reduces the development of regulatory experience and expertise, which further limits review capacity.

Sekizawa et al. (2003) and Shields et al. (2009) both document the risk of performance objectives being defined too broadly in PBFE submissions, creating a situation where a design that technically satisfies the stated objective may nonetheless fail to provide adequate protection for specific vulnerable subpopulations — including occupants with mobility impairments, non-native speakers, and individuals with cognitive disabilities. This risk is directly relevant to fire alarm system design: a notification system that achieves the stated RSET for the design occupant population may be inadequate for the actual building population if the design assumptions underrepresent the prevalence or support needs of vulnerable groups. Almejmaj et al. (2016) and Spearpoint and Maclennan (2012) provide the empirical data needed to address this risk in RSET calculations.

5.0 Discussion

5.1 PBFE in Contemporary Design Practice

The systematic review demonstrates that PBFE is a methodologically mature and technically well-supported engineering discipline with clear advantages over prescriptive compliance for complex building programs. The comparative analysis (Figure 2) quantifies these advantages across five criteria, with the strongest PBFE advantages concentrated in the criteria most directly relevant to life safety outcomes: detection response time, evacuation efficiency, and design flexibility. The prescriptive approach's retention of modest advantages in cost and regulatory acceptance reflects the structural barriers identified by Meacham (2010) rather than any fundamental analytical superiority of prescriptive methods; as PBFE practice matures and regulatory capacity develops, these barriers are expected to diminish.

The fire alarm performance criteria framework in Table 2 provides the analytical scaffold for integrating detection and notification system design into PBFE submissions in a principled and technically defensible way. The framework's organization around the ASET/RSET structure ensures that fire alarm performance is evaluated in terms of its contribution to the life safety performance objective rather than as a standalone compliance item. This integration is directly supported by the computational tools available — FDS detector response algorithms (McGrattan et al., 2019), evacuation simulation tools (Kuligowski et al., 2010), and acoustic simulation tools for emergency communications (Bukowski, 2011) — but requires practitioners who are competent across fire modelling, evacuation analysis, and alarm system design simultaneously, a multi-disciplinary competency profile that current professional development frameworks do not consistently support.

5.2 Fire Alarm Systems as Performance-Critical Engineering Variables

The case for treating fire alarm systems as performance variables rather than compliance items rests on three lines of evidence from the reviewed literature. First, computational modelling demonstrates that detector placement and technology choices have quantifiable and significant impacts on activation time, which directly affects the ASET/RSET margin in ways that prescriptive spacing rules do not adequately capture for non-standard ceiling geometries, high-momentum HVAC environments, or atrium spaces (Hadjisophocleous & Benichou, 1999; McGrattan et al., 2019). Second, occupant behavior research demonstrates that notification signal type and intelligibility have quantifiable impacts on pre-movement time — the most variable RSET components that are not captured by prescriptive notification appliance placement rules (Almejmaj et al., 2016; Ronchi & Nilsson, 2013). Third, post-incident analysis of major fire emergencies, including the NIST WTC investigation (NIST, 2005), demonstrates that alarm system performance limitations were material contributors to delayed evacuation in configurations where prescriptive compliance had been achieved.

Together, these three lines of evidence establish that prescriptive compliance with NFPA 72 and the IBC is necessary but not sufficient for fire alarm system performance in complex buildings, and that PBFE provides the analytical framework needed to identify and address performance gaps that prescriptive compliance leaves unresolved. The specific mechanisms through which PBFE adds value are the explicit modelling of detection time under realistic fire scenario conditions; the integration of notification timing into RSET calculation; the acoustic verification of speech intelligibility; and the systematic treatment of vulnerable occupant subpopulations in RSET calculations.

5.3 Harmonization with Prescriptive Codes and Regulatory Frameworks

The relationship between PBFE and prescriptive building codes is not one of replacement but of supplement and alternative. The IBC Section 104.11 and NFPA 101 Chapter 5 alternative means pathways provide the regulatory gateway through which PBFE solutions are accepted, and both require demonstration of equivalent or superior protection rather than performance superiority. Meacham (2010) argues that the harmonization of PBFE with prescriptive codes requires the development of standardized acceptance criteria — explicit performance benchmarks against which PBFE submissions can be evaluated by AHJs without requiring independent recapitulation of the full engineering analysis — analogous to the pre-approved design solutions that exist in structural engineering. ISO 23932-1 (2021) provides a partial response to this need through its framework of performance objectives and design performance criteria, but jurisdiction-specific acceptance criteria that translate these international principles into locally enforceable standards remain underdeveloped in most US jurisdictions.

5.4 Limitations

5.4.1 Uncertainty Quantification and Model Validation

The principal technical limitation of PBFE, identified across multiple reviewed sources, is the challenge of quantifying and communicating uncertainty in the model predictions on which PBFE submissions depend. FDS and CFAST simulations involve parameter uncertainty — in fire growth rates, fuel properties, ventilation conditions — that can propagate into significant uncertainty in predicted ASET values (Peacock et al., 2013; Purser & McAllister, 2016). The prescriptive approach manages this uncertainty implicitly through conservative factors built into code requirements; the PBFE approach must manage it explicitly through sensitivity analysis, conservative scenario selection, and safety margins in the ASET/RSET calculation. Current practice is highly variable in how rigorously this uncertainty management is conducted and documented, creating inconsistency in the quality and defensibility of PBFE submissions. Meacham (2010) identifies uncertainty quantification as the primary technical barrier to wider AHJ acceptance of PBFE and calls for the development of standardized probabilistic methods for fire safety design that would provide a consistent basis for evaluating model-based submissions.

5.4.2 Scope Limitations of the Review

This review is restricted to English-language sources and to the US and international normative framework (IBC, NFPA, ISO). PBFE frameworks in the UK (BS 7974), Australia (BCA Part C), New Zealand (C/VM2), and Singapore (FPSS) differ in significant ways from the US framework, particularly in their treatment of quantitative risk assessment and in their regulatory acceptance pathways. Cross-jurisdictional comparative analysis of PBFE regulatory frameworks would provide valuable evidence for harmonization efforts and for the development of international best practice standards but is outside the scope of the present review. Additionally, the rapid development of machine learning-assisted fire modelling tools — emerging in literature since 2022 — may substantially change the computational landscape for PBFE practice; this development is not yet represented in the empirical literature at sufficient volume for systematic review.

6.0 Conclusion

6.1 Summary of Contributions

This article has made four principal contributions to the performance-based fire engineering and fire alarm systems literature. First, it has conducted a systematic review establishing the methodological foundations, comparative performance evidence, and implementation barriers of PBFE, providing a comprehensive synthesis that bridges the fire alarm engineering and PBFE communities. Second, it has constructed a comparative methodology matrix (Table 1) that articulates the complementary relationship between prescriptive and PBFE approaches across six dimensions, clarifying the practical basis for choosing PBFE over prescriptive compliance for complex building programs. Third, it has developed a fire alarm performance criteria reference framework (Table 2) that situates fire alarm and detection system performance within the ASET/RSET analytical structure, providing a practical tool for engineers integrating alarm system design into PBFE submissions. Fourth, it has produced a quantitative comparative analysis (Figure 2) demonstrating PBFE's superiority in detection response, evacuation efficiency, and design flexibility, while transparently documenting the areas in which prescriptive compliance retains practical advantages.

6.2 Policy and Practice Implications

For fire protection engineers and design practitioners, the central implication is the necessity of integrating fire alarm and detection system performance into PBFE analysis as engineering variables rather than prescriptive compliance items — using the FDS detector response modules, acoustic simulation tools, and evacuation modelling capabilities available to justify system design decisions against demonstrated ASET/RSET margins. For authorities having jurisdiction, the findings support investment in reviewer training in PBFE methods and the development of jurisdiction-specific acceptance criteria that enable consistent and efficient review of performance submissions. For NFPA and ISO, the findings support the development of standardized uncertainty quantification protocols for fire modelling submissions, analogous to the reliability-based design methods that underpin structural performance codes. For building owners and institutional risk managers, the PBFE approach provides a transparent, evidence-based demonstration of the fire safety performance of complex building programs that prescriptive compliance alone cannot supply.

6.3 Future Research Directions

Six research priorities follow from the findings of this review. First, empirical validation of FDS detector response algorithms against full-scale fire test data in mechanically complex ceiling environments is needed to reduce the principal source of uncertainty in PBFE-based detector placement analysis. Second, development and validation of standardized pre-movement time distributions for diverse occupant populations — including persons with mobility impairments, cognitive disabilities, and limited English proficiency — would improve RSET calculation accuracy for the building types with the greatest vulnerability. Third, development of standardized PBFE acceptance criteria for emergency communications systems, including speech intelligibility verification protocols, would address the notification system design gap identified by Bukowski (2011). Fourth, comparative analysis of PBFE regulatory acceptance rates across jurisdictions would provide evidence for the development of harmonized international acceptance standards. Fifth, investigation of machine learning-assisted fire scenario generation and uncertainty quantification represents an emerging frontier that could substantially reduce the analytical cost of PBFE submissions. Sixth, longitudinal study of post-occupancy fire incident outcomes in PBFE-designed buildings versus prescriptive-compliant buildings would provide the definitive empirical evidence for the life safety benefits of the performance-based approach.

REFERENCES:

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