The American Journal of Engineering and Technology
ISSN 2689-0984 | Open Access

TYPE Original Research
PAGE NO. 154-162
DOI 10.37547/tajet/Volume07Issue10-19

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Prospects For Applying the Integrated Approach «Fire Safety + Engineering + Work-At-Height Technologies» For Sustainable Infrastructure Development

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OPEN ACCESS

SUBMITED 30 August 2025
ACCEPTED 25 September 2025
PUBLISHED 30 October 2025
VOLUME Vol.07 Issue 10 2025

CITATION

Valentyn Ishchenko. (2025). Prospects for Applying the Integrated Approach «Fire Safety + Engineering + Work-at-Height Technologies» for Sustainable Infrastructure Development. The American Journal of Engineering and Technology, 7(10), 154–162. https://doi.org/10.37547/tajet/Volume07Issue10-19

Abstract: Against the backdrop of rapid global urbanization and the expansion of high-rise construction, the architecture, engineering, and construction sector faces a dual imperative: to guarantee an unprecedented level of fire safety while simultaneously achieving sustainability targets. Prevailing practices in the design, construction, and operation of high-rise assets remain largely fragmented: safety subsystems, engineering solutions, and digital technologies are developed and deployed in isolation, which erodes synergistic effects and hinders the formation of a truly resilient and sustainable urban infrastructure. In response to this challenge, a holistic tripartite conceptual framework is proposed that integrates principles of fire safety, advanced engineering solutions, and high technologies. The research methodology includes a systematic literature review to inventory existing technologies and identify research gaps, as well as a qualitative comparative analysis of representative cases. The article details the key technological components of the proposed framework — Building Information Modeling (BIM), the Internet of Things (IoT), artificial intelligence (AI), and digital twins (DT). Their role is demonstrated in shaping an integrated, intelligent, and adaptive building ecosystem. The analysis identifies significant technical, organizational, economic, and educational barriers to implementing such a comprehensive approach. In conclusion, it is substantiated that the proposed integrated foundation is critically important for achieving the United Nations Sustainable Development Goals, primarily SDG 9 and SDG 11, and practice-oriented recommendations are formulated for the professional community, policymakers, and academia to accelerate the transition to a new generation of sustainable and safe vertical cities.

Keywords: Fire safety, sustainable infrastructure development, high-rise buildings and skyscrapers, Building Information Modeling, Internet of Things, digital twins, artificial intelligence, machine learning.

Introduction

The current phase of urbanization is unfolding at an unprecedented pace, radically reshaping the morphology of cities and tightening the requirements for newly created infrastructure. The concentration of population and economic activity in large agglomerations has moved high-rise construction from an aesthetic trend to a fundamental instrument of urban planning strategy. However, the shift to vertically dense development lays bare a dual problem: it is necessary to simultaneously guarantee the safety of millions of people who live and work at great heights and to satisfy the global imperatives of sustainable development. Reconciling these requirements necessitates abandoning routine approaches and forming a new paradigm for the design, construction, and operation of high-rise buildings.

Urban landscapes around the world are undergoing a qualitative transformation amid steady growth in the number of tall assets, and the near-term horizon only reinforces this trajectory. In 2025, a record 96 skyscrapers taller than 30 stories are expected to be commissioned, and the cumulative commissioning of such buildings in 2025–2027 is forecast to be 28,3% higher than in the previous three-year period [1]. This dynamic indicates that the high-rise building is becoming the dominant typology of future urban development.

Notably, the acceleration in the high-rise segment is occurring against the backdrop of a possible stagnation of the broader housing market driven by macroeconomic factors, including rising mortgage rates [2]. A pronounced market bifurcation is emerging: amid an overall slowdown in construction, the capital-intensive and highly specialized segment of high-rise assets — primarily business- and premium-class — maintains high activity [1]. Consequently, the trajectory of urban development will increasingly be determined by technologically complex and expensive assets, for which requirements for safety and operational reliability increase nonlinearly. This concerns not only the increase in the number of buildings but also the complication of their architectural and engineering profile. The historical time series of the Council on Tall Buildings and Urban Habitat (CTBUH) record an exponential increase in the number of assets over 200 m (tall) and 300 m (supertall) on the global map — from Asia to North America — radically changing city skylines [3].

The concentration of people and critical infrastructure within vertical volumes forms a complex risk profile in which priority belongs to fire safety. Global data underscore the urgency of the issue: according to the CTIF report for 2023, in the surveyed countries with a population of 1,5 billion people, 3,1 million fires were recorded, resulting in 17 400 deaths and 45 000 injuries [7]. Specific statistics for high-rise buildings are also alarming: according to the National Fire Protection Association (NFPA) in the United States, an annual average of 14 500 fires in high-rise buildings is recorded. The tragedy in Valencia in February 2024, which claimed 10 lives, served as a vivid reminder of the catastrophic potential of such incidents [8].

Fire risk in a high-rise building is fundamentally different from risks in low-rise buildings and cannot be reduced to simple scaling. Physical effects such as the stack effect in vertical shafts, capable of causing smoke spread throughout a 100-meter structure within 30 seconds, significantly increased evacuation time, and the limited capabilities of external firefighting units form a nonlinear risk structure [10]. Accordingly, a shift is required from prescriptive codes to adaptive, intelligent, and performance-oriented safety systems.

In parallel, vertical urban infrastructure must align with global sustainable development agendas. Infrastructure solutions directly affect the achievement of approximately 72% of the 169 targets within the 17 United Nations Sustainable Development Goals [11, 12]. This creates a dual imperative: buildings must be simultaneously exceptionally safe and highly efficient from a sustainability standpoint — a task that fragmented, narrowly disciplinary design and management approaches fail to meet.

Addressing this challenge requires a paradigm shift: from fragmented and narrowly specialized measures to a holistic integrated concept that ensures the alignment of fire safety, engineering principles, and digital technologies at all stages of the building life cycle.

The author's hypothesis is that the integrated triadic concept fire safety + engineering + high technologies provides a higher level of safety, controllability, and sustainability for high-rise infrastructure than fragmented approaches and is critically important for achieving SDG 9 and SDG.

The scientific novelty lies in the fact that, for the first time, a comprehensive framework is proposed that systematically integrates PBD, BIM, IoT, AI/ML, digital twins, and robotics across all stages of the life cycle of high-rise assets, supported by a systematic review, a comparison of three cases, and a taxonomy of barriers with practical pathways to overcome them.

The aim of the article is to substantiate and describe in detail the integrated foundation of the fire safety + engineering + high technologies concept, to inventory the key technologies and their roles, to verify its applicability on real examples, and to formulate recommendations to accelerate the transition to sustainable and safe vertical cities.

Methods

The methodological framework of the study rests on a systematic literature review conducted in strict accordance with recognized protocols. Within the review, findings from studies in leading indexed databases (Scopus, Web of Science) are synthesized, covering the domains of sustainable infrastructure, fire safety engineering, and integrated digital technologies (BIM, IoT, AI). This theoretical layer is purposefully complemented with a qualitative comparative examination of three landmark cases — Burj Khalifa, Shanghai Tower, and The Edge — so as to verify the proposed conceptual framework against real-world practice.

The remainder of the article is structured sequentially: first, the theoretical premises are presented; then, the integrated concept is elaborated in detail; thereafter, its practical implementation is analyzed. In conclusion, barriers to implementation are discussed and directions for future research are outlined.

Results And Discussions

To build a reliable integrated conceptual foundation, it is first necessary to delineate its key pillars. Sustainable infrastructure is understood as infrastructure that is designed, constructed, and operated with a holistic consideration of socioeconomic and ecological and environmental factors for the preservation and improvement of the natural environment [12]. Its direct alignment with the UN 2030 Agenda is evident: it is a core condition for achieving SDG 9 (Industry, Innovation and Infrastructure), oriented toward creating resilient and sustainable infrastructure, and SDG 11 (Sustainable Cities and Communities), aimed at forming inclusive, safe, resilient, and sustainable cities [21]. A significant contribution to the realization of these goals is made by smart building technologies, which ensure optimization of resource use, waste reduction, and improvement of the quality of the urban environment [26].

The notions of sustainable infrastructure and smart buildings essentially converge. Sustainability sets the what (rational resource use, resilience, well-being), whereas smart technologies determine the how (real-time data, predictive analytics, automation). The absence of an integrated conceptual framework hinders the full realization of this natural synergy, giving rise to projects that turn out to be green but not smart, or smart but not systemically sustainable.

The technological high-tech block of the proposed concept is developing rapidly. Building Information Modeling (BIM) represents a process of managing building information throughout the entire life cycle based on a 3D model [14]. Its functionality goes far beyond visualization and encompasses 4D (time), 5D (cost), and 6D (sustainability), which turns BIM into a tool for optimizing design solutions and detecting clashes [13].

The Internet of Things (IoT) is a network of physical devices equipped with sensors that collect and transmit data in real time. In buildings, these include temperature, smoke, and occupancy sensors, as well as sensors of system performance, enabling continuous monitoring and automated responses.

Artificial intelligence (AI) and machine learning (ML) constitute the analytical core that processes the data volumes generated by BIM and IoT. Practical applications include predictive maintenance, pattern recognition for risk assessment, and optimization of building operating modes to enhance energy efficiency and safety [12].

Digital twins (DT) are dynamic virtual replicas of a physical object that integrate BIM models with real-time IoT data streams. DT enable complex simulations, scenario planning (for example, evacuation drills), and predictive analysis of building performance and resilience [13].

Traditional prescriptive fire safety codes exhibit limitations when applied to complex supertall structures: they are inflexible and often overlook unique structural solutions and fire dynamics [9, 11]. In response, a performance-based design (PBD) approach has taken shape, in which target safety indicators are formulated and then the compliance of a specific project with these targets is demonstrated using engineering methods, which opens greater opportunities for flexibility and innovation [11].

The transformation under consideration is not merely an adjustment of the regulatory environment but a shift of the epistemological paradigm, without which the integration of high-technology solutions is impossible. Whereas prescriptive norms aim at adherence to fixed prescriptions, PBD focuses on the presentation of verifiable evidence of achieved performance. This by definition requires reliance on advanced means of computational modeling, simulation, and continuous monitoring, which are provided by BIM, digital twins, and IoT. In this way, the expansion of PBD itself generates demand for the technologies that lie at the core of the proposed concept, forming a causal linkage between the methodology and the toolkit.

Below is presented a conceptual model of an integrated foundation Fire Safety + Engineering + High Technologies. This foundation is described as a multi-level architecture in which each technological component performs an autonomous yet interfaced function throughout the entire building life cycle. The proposed concept is not a sum of elements but a synergistic configuration in which the contribution of each component reinforces the others.

Fire safety formulates critical target indicators of operational performance (for example, protection of life, safeguarding of property values). Engineering (structural, mechanical, electrical) provides the material systems and design principles for achieving these indicators. Technologies function as a nervous system, integrating, controlling, and optimizing the physical subsystems to ensure dynamically and efficiently the required performance throughout the life cycle. Further, table 1 describes the features of technologies in the integrated conceptual foundation.

Table 1. Key technologies in the integrated conceptual framework (compiled by the author based on [4, 5, 13, 16, 25]).

Technological component	Core function within the framework	Contribution to fire safety	Contribution to sustainability
BIM	Centralized 3D information model; lifecycle data repository.	Detection of clashes in fire suppression systems; storage of fire resistance data; basis for evacuation simulation.	6D BIM for life-cycle analysis; optimization of material use; reduction of construction waste.
IoT	Real-time acquisition of data from the physical environment.	Early detection of fire/smoke; real-time occupancy monitoring; equipment condition monitoring.	Real-time monitoring of energy and water consumption; data for predictive maintenance; optimization of space utilization.

AI / ML	Data analytics; pattern recognition; predictive modeling.	Predictive maintenance for fire suppression systems; dynamic risk assessment; intelligent video-based fire detection.	Optimization of HVAC/lighting for energy efficiency; forecasting of resource demand.
Digital twin	Real-time dynamic virtual replica of the building.	Simulation of fire/smoke spread; testing of dynamic evacuation strategies; provision of situational awareness for first responders.	Simulation of energy performance under varying conditions; optimization of operational efficiency.
Robotics	Automated physical inspection and maintenance.	Inspection of facade/structural integrity; access to hazardous areas after an incident.	Reduction of risks/costs for at-height maintenance; enabling proactive repair of building envelope systems.

Having examined the theoretical component of the study, it is appropriate to proceed to the analysis of practical cases, using three supertall/high-tech buildings that demonstrate real implementations of the key principles and their stepwise progression toward an integrated model.

The first example is the Burj Khalifa. This facility is characterized by a multilayer, redundant safety architecture: a branched system of sprinklers and risers supplied from large reservoirs and pump units; a cascade of sealed refuge zones every 25–30 floors providing safe points for waiting and regrouping; and also the first use in the world of programmable evacuation elevators in a supertall building. High-performance fire-resistant materials and FP series cable lines played a critical role.

The Burj Khalifa demonstrates a radically consistent orientation toward preservation of life, implemented through a prescriptive plus approach: the regulations (IBC, NFPA 101) are not merely complied with but intentionally exceeded. Although the calculations relied on the classical engineering methodology without a dynamic digital twin, the outcome represents the upper bound of the effectiveness of the traditional paradigm and the scale of the challenge that the integrated framework is intended to address more economically and controllably [22, 23].

The next example is Shanghai Tower. This case illustrates coordinated integration of disciplines already at the design stage for the simultaneous attainment of safety and sustainability. The specific features of this facility are - a twisted double-skin facade — not a decorative gesture but an aerodynamic strategy: wind tunnel tests and numerical models confirmed a 24% reduction in wind loads, which yielded significant savings on load-bearing systems and reduced material intensity. The interfacade space functions as a thermal buffer, lowering heating and cooling demands. The structural scheme is integrated with a performance-based fire safety strategy: FDS modelling was employed to analyze fire and smoke behavior in the complex atrium volumes between the two curtain walls [11, 15].

Shanghai Tower is an indicator of how advanced modelling (a de facto precursor to digital twins) makes it possible to optimize a building across multiple criteria simultaneously: structural stability, energy efficiency, fire safety. The synergy of disciplines here is not a by-product but a principle underlying the proposed conceptual model; the use of AI in materials selection and energy modelling further consolidates this logic.

The third case is The Edge. This case is the closest existing implementation of the High Technologies pillar, aimed at operational efficiency and sustainability through a dense IoT infrastructure. The building holds a record BREEAM rating Outstanding — 98,4%. Its LED lighting system integrates 28 000 sensors that track motion, temperature, illuminance, and presence. Data streams are consolidated in the BMS, which optimizes operating modes in real time: lights turn off in unoccupied spaces, HVAC adapts to actual occupancy, and cleaning schedules are reconfigured according to usage trajectories. A mobile application provides employees with personalized light and temperature settings at their workstations. Such a data-driven mode reduces electricity consumption by approximately 70% relative to the typical office stock.

The Edge is an illustrative lesson on the digital backbone and the intelligence layer: a dense sensor network coupled with smart control delivers unprecedented levels of sustainability and user comfort. Although the project focus is sustainability, the same infrastructure (sensors, network, analytics) naturally scales to fire safety domains, including dynamic evacuation routing based on the current occupancy picture [6, 16].

Table 2 presents a comparative analysis of the features of the considered facilities.

Table 2. Comparative analysis of real estate assets (compiled by the author based on [3, 11, 17, 18, 21]).

Metric	Burj Khalifa (Dubai)	Shanghai Tower	The Edge (Amsterdam)
Height / Scale	828 m / 163 floors (Supertall)	632 m / 128 floors (Supertall)	40 000 sq m / 14 floors (High-rise)
Primary innovation focus	Life safety and large-scale evacuation	Integrated structural and sustainable design	IoT-based sustainability and operations
Key Safety Technologies	Refuge floors; evacuation elevators; pressurized stairwells; advanced fire pumps.	Performance-based fire safety design; FDS modeling of atria; double-skin facade as buffer.	Integrated BMS for safety monitoring; potential use of IoT data.
Key Sustainability Technologies	High-performance glazing.	Facade reducing wind load; double thermal buffer; geothermal systems.	BREEAM 98,4%; 28 000 sensors; solar panels; rainwater harvesting; AI-optimized BMS.
Demonstrated principle	Apex of engineering safety in the pre-digital-twin era.	Synergy of performance-based engineering at the design stage.	Embodiment of an IoT-based digital backbone for operational efficiency.

The following specific directions of action are delineated, aimed at the practical implementation of the integrated conceptual framework (see fig.1).

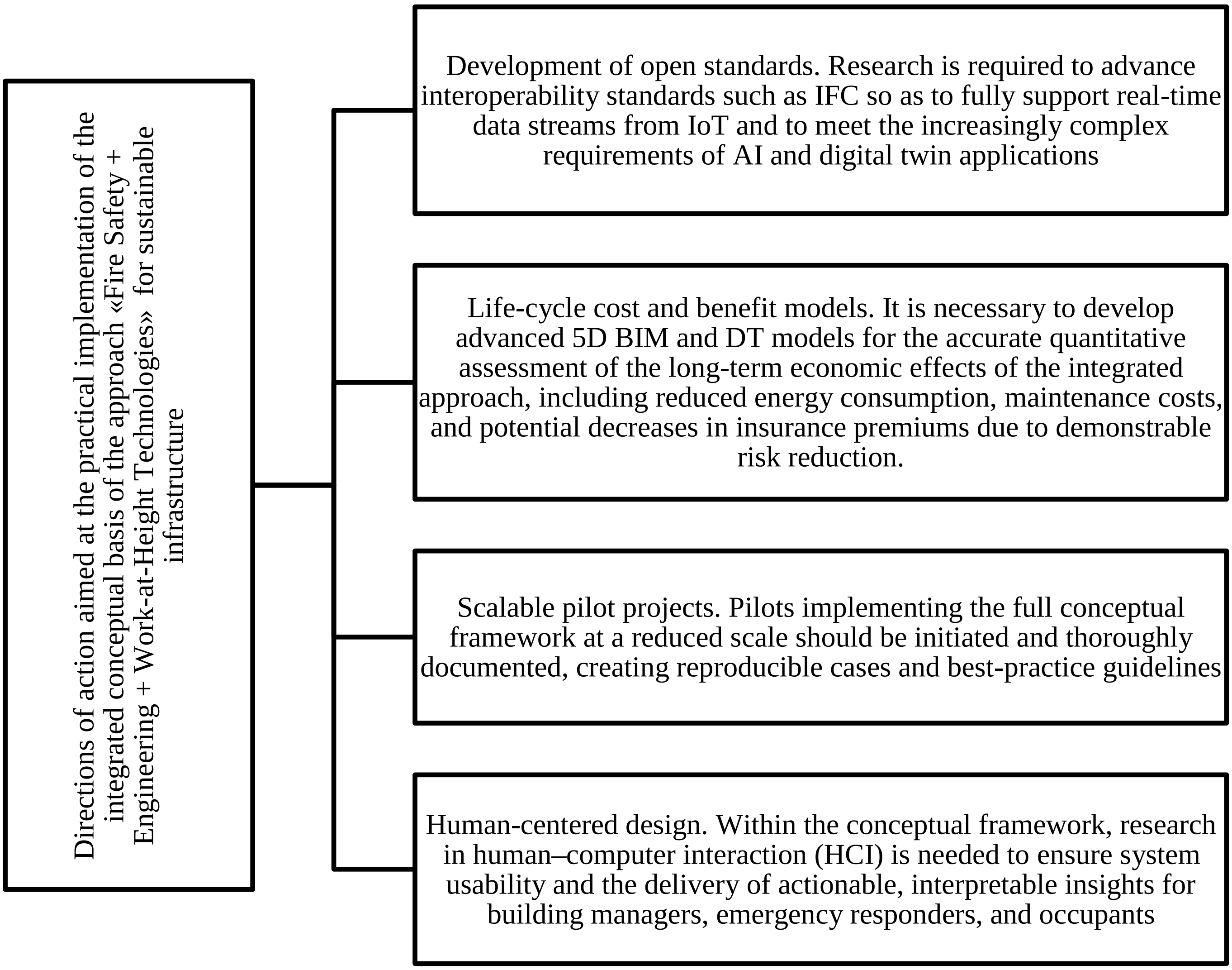

Fig. 1. Directions of action aimed at the practical implementation of the integrated conceptual basis of the approach «Fire Safety + Engineering + Work-at-Height Technologies» for sustainable infrastructure (compiled by the author based on [19, 20, 24]).

Thus, the proposed conceptual framework is situated within the broader context of Industry 4.0. The integration of cyber-physical systems (digital twins), IoT, and AI is a distinguishing feature of this industrial transformation. The logical horizon of evolution is the cognitive building, an asset that not only automates responses according to predefined rules but, by means of AI, learns, adapts, and forecasts user needs and environmental changes, becoming truly autonomous and fault-tolerant.

Conclusion

Thus, it can be said that sustainable infrastructure and smart buildings are not parallel but convergent trajectories that require a single integrated foundation. Such a foundation must simultaneously uphold sustainability targets (resource efficiency, resilience, well-being) and the operational mechanisms for achieving them (real-time data, predictive analytics, automation). The linkage aligns directly with SDG 9 and 11: this is not about adding a green layer to traditional projects, but about a systems architecture in which engineering, safety, and digital technologies operate as a single organism. The absence of a common framework leads to imbalances — green-mad or smart-unsustainable solutions — and to missed synergy across the entire life cycle.

The technical core of such a foundation is formed by BIM (including 4D/5D/6D), IoT, AI/ML, digital twins, and robotics, which act respectively as the repository of asset knowledge, the sensory organ, the analytical brain, the dynamic model, and the actuating periphery. The transition to performance-based design (PBD) is a critical methodological shift: it moves the discussion from the plane of prescriptive compliance to the plane of demonstrated performance. This automatically increases the demand for high-fidelity simulation, validation, and continuous monitoring, which the named technologies provide; the methodology and toolset form a causally conditioned cycle of mutual reinforcement. As a result, the same digital loops simultaneously enhance fire safety (early detection, scenario-based evacuation, predictive maintenance) and sustainability (energy efficiency, resource intensity, extension of service life).

Case analysis confirms a phased evolution toward an integrated model. Burj Khalifa demonstrates the upper bound of a prescriptive-plus approach: exceptional safety architecture, exceeding codes, but limited digital dynamics — an important benchmark and at the same time the limit of the traditional paradigm. Shanghai Tower shows the power of early interdisciplinary coordination: an aerodynamically driven double-skin facade, a 24% reduction in wind loads, the use of FDS and PBD — a prototype of digitally grounded engineering in which safety, sustainability, and structure are co-optimized. The Edge illustrates the digital backbone of operations: a record BREEAM 98,4%, ~28 000 sensors, and a data-driven control regime delivering ≈70% electricity savings; the same sensor layer readily scales to dynamic safety and evacuation. Together these examples delineate the trajectory from static regulatory sufficiency to a living, learning system.

The implementation roadmap requires not only engineering but also institutional actions. Open standards and interoperability are needed (extending IFC for real-time streams), life-cycle quantitative models in 5D BIM/DT to justify CAPEX↔OPEX↔risks, scalable pilots with replicable practices, as well as human-centered interface design for managers, service teams, and users. It is important to address in advance the legal and commercial aspects of data ownership and liability; otherwise vendor lock-in will block the systemic effect. Embedding this foundation in the context of Industry 4.0 shifts the horizon toward the cognitive building — an asset that adapts and predicts, providing safety and sustainability as a continuous, metrics-verified function. Thus, the integrated concept Fire Safety + Engineering + High Technologies is not an option but a necessary condition for the steered progress of the urban environment.

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