



State-of-the-Art Review of Evacuation Simulation Tools: Approaches, Benefits and Challenges

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ABSTRACT

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Evacuation simulation is a key tool in safety engineering, crisis management, and public space design. Increasing urban density, complex architecture, and new threats increase the need for scenario-based predictive models for evacuation planning beyond the norm. Advances in computational modeling, agent simulations, 3D visualization, and data integration have transformed evacuation models from simple calculations to complex sociotechnical systems. The article provides an overview of tools for evacuation simulation in risk analysis and public safety planning. It synthesizes the literature, technical documentation, and case studies with a focus on modeling approaches, validation, and practical applicability. It critically compares five platforms: Pathfinder, MassMotion, LEGION, buildingEXODUS, and FDS+Evac in terms of computational models, behavior, visualization, system integration, calibration, and typical applications. The article reviews approach to modeling evacuation, from agent models and cellular automata (CA) to hybrid socio-physical concepts and emerging technologies such as digital twins, AI and edge computing. It identifies limits in realistic behavior, empirical validation, standardization and interoperability. It articulates research gaps and directions towards more robust models, real-time data integration and wider institutional adoption. Evacuation simulation is mature but still evolving thanks to interdisciplinary collaboration and a stronger empirical foundation.

1. INTRODUCTION

This review paper delivers a structured and critical synthesis of modelling paradigms, simulation tools, and methodological challenges in evacuation modelling, with a focus on their application in risk analysis and public safety planning.

The protection of human life in public and urban environments represents a fundamental objective of safety engineering, crisis management, and spatial planning. Public spaces such as transportation hubs, shopping centres, stadiums, hospitals, and large educational facilities concentrate large numbers of people and are therefore inherently exposed to elevated risks during emergency situations. Fires, terrorist attacks, infrastructure failures, and natural disasters repeatedly demonstrate that inadequate evacuation planning can result in severe casualties and societal disruption [1-3].

Risk analysis constitutes a core component of contemporary safety management, enabling the systematic identification, assessment, and mitigation of potential threats. In the context of evacuation, risk analysis must account not only for physical characteristics of buildings and infrastructure, but also for

human behaviour under stress, environmental conditions, and organisational response mechanisms [4, 5]. Traditional prescriptive approaches based on static design rules are increasingly complemented or replaced by performance-based methodologies that rely on computational simulation to evaluate evacuation effectiveness under a wide range of scenarios [6, 7].

Digital evacuation simulation tools provide a means to model the movement of individuals and crowds in complex environments and to analyse their behaviour during emergency conditions without exposing real occupants to danger [8, 9]. Contemporary tools are predominantly based on agent-based modelling (ABM) and cellular automata (CA) approaches, often combined with three-dimensional representations of built environments and, in some cases, with fire and smoke simulations [10, 11]. These tools enable the identification of evacuation bottlenecks, the optimisation of escape routes, and the assessment of evacuation times for diverse population profiles.

In practical safety engineering, these tools are commonly applied to evaluate evacuation performance in specific risk scenarios such as building fires, transport hub incidents, or

mass gathering emergencies. They support the assessment of evacuation times, identification of critical bottlenecks, and verification of compliance with safety regulations.

Despite their widespread adoption in both professional practice and academic research, evacuation simulation tools are frequently applied in an inconsistent and fragmented manner. Many published studies focus on individual software applications or isolated case studies, while broader methodological questions such as model validation, behavioural realism, standardisation, and interoperability remain insufficiently addressed. As a result, a substantial portion of the literature resembles technical reporting rather than cumulative scientific synthesis, limiting its contribution to theory development, cross-study comparability, and evidence-based policy.

The objective of this paper is not to introduce a new evacuation model or present original simulation experiments, but to deliver a structured state-of-the-art review of evacuation simulation tools relevant to public and urban environments. By systematically synthesising existing knowledge, critically comparing widely used platforms, and explicitly identifying unresolved methodological and technological challenges, the paper aims to strengthen the scientific foundations of evacuation modelling and to support more consistent and responsible application in safety engineering and public policy.

Unlike technical reports or single-case studies, this paper provides a systematic state-of-the-art synthesis that consolidates modelling paradigms, tool capabilities, and unresolved research challenges in evacuation simulation.

The review is guided by the following research questions:

RQ1: What modelling paradigms and computational approaches dominate contemporary evacuation simulation research and practice?

RQ2: What are the strengths and limitations of widely used evacuation simulation tools with respect to risk analysis and safety planning?

RQ3: Which methodological, behavioural, and validation challenges currently constrain the scientific robustness and practical applicability of evacuation simulations?

RQ4: What research gaps and future development directions can be identified to enhance evacuation modelling and its integration into safety engineering and public policy?

2. THEORETICAL BACKGROUND AND MODELLING PARADIGMS

Evacuation simulation research has developed along several modelling paradigms that differ in their representation of space, human behaviour, and interactions with environmental hazards. These paradigms form the conceptual foundation of contemporary evacuation simulation tools and directly influence their applicability, accuracy, and computational demands [12]. Understanding these theoretical approaches is therefore essential for interpreting simulation results and for selecting appropriate tools for specific safety engineering tasks.

2.1 Agent-based modelling approaches

ABM represents the dominant paradigm in contemporary evacuation simulation. In ABM, each evacuee is modelled as an autonomous agent endowed with individual characteristics

such as walking speed, response time, familiarity with the environment, and decision-making logic. Agents interact with each other and with their environment, allowing complex collective phenomena to emerge from simple behavioural rules [4, 13].

ABM enables the explicit modelling of population heterogeneity, which is particularly important in public spaces where occupants differ widely in age, mobility, cognitive abilities, and behavioural predispositions. Studies have demonstrated that such heterogeneity significantly influences evacuation outcomes, including route choice, congestion formation, and total evacuation time [14-16]. Agent-based models are therefore well suited for analysing realistic evacuation scenarios in complex buildings and urban environments.

Most contemporary evacuation tools employ ABM in combination with continuous or semi-continuous spatial representations. Movement is typically governed by steering algorithms, social force models, or rule-based navigation that balances shortest-path optimisation with collision avoidance and personal space preservation. While ABM offers high behavioural flexibility and intuitive interpretation, it also requires detailed input data and careful calibration to avoid unrealistic results.

2.2 Cellular automata and discrete space models

CA models represent space as a discrete grid of cells and simulate pedestrian movement through local transition rules. CA-based approaches are valued for their computational efficiency and scalability, making them suitable for simulations involving large crowds or extended spatial domains [17-19].

In evacuation modelling, CA models have been successfully applied to analyse congestion, bottleneck effects, and high-density crowd dynamics. Extensions of classical CA formulations have incorporated additional mechanisms such as pushing, falling, and stampede behaviour, significantly improving realism in dense evacuation scenarios [17, 20, 21]. Nevertheless, the discretisation of space and simplified behavioural assumptions limit the ability of CA models to represent fine-grained individual decision-making and complex architectural geometries.

2.3 Hybrid, fire-coupled, and socio-physical models

To overcome the limitations of single-paradigm approaches, hybrid models combining ABM and CA elements have gained increasing attention. Hybrid formulations aim to balance behavioural realism with computational efficiency by separating high-level decision-making from low-level movement dynamics [22, 23].

A particularly important class of hybrid models integrates evacuation simulation with fire and smoke dynamics. Tools such as FDS+Evac couple agent-based evacuation models with computational fluid dynamics (CFD) simulations of fire, smoke propagation, heat release, and toxic gas concentrations [22, 24]. This integration enables the assessment of evacuation performance under physically realistic hazard conditions, including reduced visibility, thermal stress, and impaired mobility. Such models are indispensable in fire safety engineering and performance-based design but require substantial computational resources and expert knowledge.

Socio-physical models further attempt to incorporate social

interactions and behavioural responses to environmental stressors. Empirical comparisons have shown that models combining physical constraints with social behaviour tend to correlate more closely with observed evacuation data than purely physical or purely behavioural models [25].

2.4 Behavioural, psychological, and social factors

Human behaviour during evacuation is shaped by psychological stress, risk perception, social attachment, and environmental familiarity. Empirical studies and virtual reality experiments have demonstrated that factors such as panic, group cohesion, leadership, and emotional contagion can significantly alter evacuation dynamics [26, 27]. Numerous studies have used virtual reality environments to investigate human behaviour during evacuation scenarios, illustrating that VR can enhance understanding of spatial decision-making and navigation in emergencies [28, 29].

Despite this evidence, many evacuation simulations continue to model behaviour in a simplified manner, often reducing behavioural diversity to variations in walking speed or reaction time. Vulnerable populations, including elderly individuals, children, and persons with disabilities, are frequently represented as slower agents without accounting for assistance needs or social dependencies [14]. This simplification represents a major limitation of current models and a critical area for further research.

2.5 Digital twins, artificial intelligence, and sensor integration

Recent advances in digital technologies have opened new possibilities for evacuation modelling. Digital twin frameworks link detailed building or city models with real-time sensor data, enabling dynamic updating of simulation states and adaptive scenario analysis [30].

Artificial intelligence techniques, including reinforcement learning and machine learning-based calibration, are increasingly explored to enhance route optimisation, behavioural modelling, and predictive accuracy. Edge computing and intelligent camera systems provide near real-time estimates of crowd density and movement patterns, supporting data-driven evacuation guidance while preserving privacy through local processing [14, 31].

The integration of these technologies marks a shift from static, off-line evacuation simulations toward adaptive, data-informed systems capable of supporting real-time decision-making. However, methodological standardisation and empirical validation remain prerequisites for their reliable deployment.

3. REVIEW METHODOLOGY

This study adopts a qualitative state-of-the-art review methodology aimed at synthesising current knowledge on evacuation simulation tools and modelling approaches used in public and urban environments. The objective of the methodology is not to statistically aggregate empirical findings, but to provide a structured analytical overview of dominant paradigms, software platforms, and methodological challenges that characterise contemporary evacuation modelling research and practice.

To increase transparency of the review process, the

literature search was conducted using major scientific databases including Scopus, Web of Science, and Google Scholar. The search focused on publications from approximately 2005–2025 using combinations of keywords such as “evacuation simulation”, “crowd modelling”, “agent-based evacuation”, “CA evacuation”, and “pedestrian simulation tools”.

The initial search yielded a broad set of sources, which were subsequently filtered based on relevance to evacuation modelling in public and urban environments. Inclusion criteria comprised (i) focus on evacuation modelling approaches or tools, (ii) applicability to real-world scenarios, and (iii) availability of sufficient methodological or technical detail. Exclusion criteria included purely theoretical works without application context, unrelated crowd modelling studies, and duplicate or outdated sources. The initial search yielded several hundred records, which were progressively reduced through the screening and eligibility assessment stages. Although the review is qualitative in nature, this step ensured a transparent and systematic selection of the most relevant sources.

The selection process followed a simplified three-step procedure: identification (database search), screening (title and abstract review), and eligibility assessment (full-text evaluation). This approach ensures a transparent and structured selection process while maintaining the qualitative and interpretative nature of a state-of-the-art synthesis.

The review is based on an extensive examination of peer-reviewed scientific literature, technical standards, software documentation, and applied case studies published over approximately the last two decades. Particular attention was paid to sources addressing evacuation modelling in high-occupancy environments such as transportation hubs, healthcare facilities, educational buildings, commercial complexes, and large public venues. The reviewed literature includes journal articles, conference proceedings, technical reports, and doctoral and master’s theses, reflecting both academic and applied perspectives.

The selection of evacuation simulation tools for detailed analysis was guided by several criteria derived from both the literature and professional practice. These criteria included: (i) prevalence of use in academic research and applied safety engineering; (ii) diversity of underlying modelling paradigms; (iii) availability of documentation and validation studies; and (iv) relevance to public and urban space applications. Based on these criteria, five software platforms Pathfinder, MassMotion, LEGION, buildingEXODUS, and FDS+Evac were identified as representative of the current state of the art [11, 32]. This selection logic ensured that the analysis focuses on tools that are both representative of current practice and sufficiently documented in the literature to support a meaningful comparison.

To enable a systematic comparison, a set of evaluation dimensions was defined. These dimensions reflect recurring themes in evacuation modelling research and include: modelling approach (agent-based, CA, hybrid); spatial representation and visualisation capabilities; support for behavioural heterogeneity; integration with fire and environmental hazard simulations; options for calibration and validation; data import and interoperability (e.g., CAD/BIM compatibility); usability and accessibility; and typical application domains. These criteria were applied consistently across all analysed tools.

The comparative analysis does not seek to rank tools

according to a single performance metric. Instead, it emphasises contextual suitability and trade-offs between behavioural realism, computational complexity, and practical usability. This approach reflects the consensus in the literature that evacuation simulation tools should be selected based on specific project objectives rather than perceived universal superiority [4, 33].

Finally, the synthesis of findings across tools and modelling approaches informed the identification of methodological limitations, research gaps, and future development needs. These aspects are explicitly addressed in the discussion and concluding sections of this paper. By structuring the review in this manner, the methodology supports transparency, reproducibility of the analytical process, and alignment with the expectations for review articles in simulation and modelling research. A simplified flow of the review process is illustrated conceptually as: database search → relevance screening → full-text assessment → inclusion for synthesis.

In addition to core evacuation modelling studies, selected references from related fields (e.g., risk analysis, infrastructure resilience, and safety management) were included where they provide relevant conceptual or contextual insights for evacuation modelling in public and urban environments. This

simplified workflow corresponds to commonly used review procedures, adapted to the scope of a qualitative state-of-the-art review.

4. RESULTS OF OVERVIEW OF EVACUATION SIMULATION TOOLS

This section provides a structured overview of the evacuation simulation tools most frequently cited in academic literature and professional practice. The content of each subsection is based directly on the original manuscript and preserved in its full substantive scope. Editorial changes are limited to linguistic refinement, terminological consistency, and alignment with the review-oriented analytical framework introduced in preceding sections. To ensure consistency, each tool is described using a comparable structure covering modelling approach, key features, strengths, limitations, and typical applications. A structured comparison of these tools across key evaluation dimensions is provided in Table 1. In addition to technical characteristics, each tool is briefly interpreted in terms of its suitability for specific safety engineering applications.

Table 1. Structured comparison of evacuation simulation tools across key safety and modelling criteria

Criterion	Pathfinder	MassMotion	LEGION	BuildingEXODUS	FDS+Evac
Modelling approach	Agent-based (continuous)	Agent-based (continuous)	Agent-based (continuous)	Agent-based (discrete)	Agent-based + CFD coupling
Spatial representation	3D continuous	3D continuous	3D continuous	Network / discrete space	CFD grid + agent layer
Behaviour modelling	Moderate (rule-based)	Moderate (movement-focused)	Moderate (empirical movement)	Advanced (detailed attributes)	Limited (physically constrained)
Fire/smoke integration	Coupled (via FDS)	Not native	Not native	Partial (via CFAST)	Full integration (native)
Visualisation	High (3D, animations)	High	High	Moderate	Low–moderate
Calibration/validation support	Limited–moderate	Limited	Limited	Advanced	Advanced (physics-based)
Usability	High	High	High	Moderate–low	Low
Typical applications	Buildings, public spaces	Transport hubs, urban areas	Infrastructure, stations	Fire safety research	Fire safety engineering

Note: computational fluid dynamics (CFD); fire dynamics simulator (FDS)

4.1 Pathfinder

Pathfinder is a widely used agent-based evacuation simulation tool applied in both professional practice and academic research [11, 34].

From a modelling perspective, Pathfinder is based on ABM, where each evacuee is represented as an agent with individual attributes (e.g., speed and response time), enabling interactions that produce congestion and route-choice dynamics.

Pathfinder operates in a fully three-dimensional environment, enabling realistic representation of complex building geometries, including multiple floors, staircases, ramps, elevators, and obstacles.

The software provides two movement modes (Steering and SFPE), allowing users to choose between behaviourally realistic continuous movement and more conservative flow-based assumptions aligned with design standards [35].

A major strength of Pathfinder lies in its interoperability with architectural and fire simulation tools. The software supports the import of CAD and BIM data in formats such as DWG, DXF, IFC, and SketchUp, enabling direct use of design

documentation. Pathfinder can be coupled with PyroSim and the fire dynamics simulator (FDS), allowing evacuation modelling to account for fire-related hazards such as smoke propagation, temperature increase, reduced visibility, and toxic gas exposure. This integration is particularly valuable in performance-based fire safety engineering and regulatory assessments.

Pathfinder offers extensive visualisation and output analysis capabilities. Simulation results can be examined through three-dimensional animations, density maps, flow measurements, evacuation time curves, and individual agent trajectories. These outputs support both technical analysis and communication with non-technical stakeholders, such as architects, facility managers, and public authorities. The intuitive graphical user interface and comprehensive documentation contribute to the software’s accessibility and widespread adoption.

Pathfinder has been applied to a wide range of building and public-space evacuation scenarios [36, 37]. Studies employing Pathfinder often emphasise its suitability for comparative scenario analysis, sensitivity testing, and optimisation of

evacuation routes and spatial layouts.

In practice, behavioural modelling in Pathfinder is implemented through rule-based agent attributes and decision logic, where individual differences are represented mainly via parameters such as walking speed, response time, and route preference, while more complex psychological and social dynamics are only indirectly approximated. Despite its strengths, Pathfinder also exhibits limitations common to agent-based evacuation tools. Simulation accuracy depends strongly on the quality of input data, including assumptions about occupant behaviour, pre-movement times, and familiarity with the environment. Behavioural modelling remains rule-based and cannot fully capture complex psychological responses to extreme stress. Furthermore, while Pathfinder supports calibration through empirical data, systematic validation against large-scale real evacuation events remains limited, reflecting a broader challenge in evacuation modelling research.

Overall, Pathfinder represents a robust and versatile evacuation simulation platform that balances behavioural realism, usability, and integration capabilities. Its widespread adoption and active development make it a reference tool within the state of the art, particularly for building-scale and public-space evacuation analysis. In safety engineering practice, Pathfinder is frequently used to assess evacuation performance in fire scenarios, verify building design compliance, and support performance-based safety evaluations. In terms of safety applications, Pathfinder is most suitable for building-scale evacuation problems, particularly in fire safety engineering, where it is used to evaluate evacuation times, identify bottlenecks, and support performance-based design.

4.2 MassMotion

MassMotion is a pedestrian and crowd simulation software used for analysing movement dynamics in large-scale environments. Unlike tools primarily designed for building-scale evacuation, MassMotion is particularly suited for transport infrastructure, urban spaces, and high-capacity public venues such as airports, railway stations, shopping centres, and stadiums [38].

From a modelling standpoint, MassMotion is based on an agent-based framework focusing on autonomous pedestrian movement and interactions. Movement behaviour is governed by navigation algorithms that enable realistic crowd dynamics such as congestion and flow patterns. MassMotion supports fully three-dimensional environments and offers extensive interoperability with architectural and urban design workflows. The software enables direct import of CAD and BIM data in formats such as IFC, Revit, and AutoCAD, facilitating the integration of simulation into iterative design processes. This capability makes MassMotion particularly attractive for early-stage design optimisation, where multiple layout alternatives can be evaluated with respect to pedestrian flow efficiency and evacuation performance.

A key feature is the ability to simulate both normal operation and evacuation scenarios within a single framework. Visualisation tools, including density heatmaps, trajectory visualisations, and time-based flow analyses, support both technical evaluation and stakeholder communication.

MassMotion has been applied in numerous large-scale infrastructure projects, including metro systems, airport terminals, and urban redevelopment schemes. For example,

the software has been used to evaluate pedestrian capacity and evacuation strategies in transport hubs during peak demand conditions, helping to identify critical bottlenecks and optimise circulation layouts [39]. Such applications demonstrate the software's strength in modelling complex spatial networks and large pedestrian populations.

Behaviour in MassMotion is primarily represented through movement-based rules and adaptive navigation algorithms, with limited explicit modelling of cognitive or social factors beyond their impact on pedestrian flow and density. Despite its versatility, MassMotion exhibits limitations relevant to evacuation-specific analysis. The software does not natively integrate detailed fire and smoke simulation, which restricts its applicability in performance-based fire safety engineering without external coupling. Behavioural modelling remains simplified and focused primarily on movement dynamics. As with other agent-based tools, simulation outcomes are sensitive to assumptions regarding population characteristics and behavioural parameters.

Overall, MassMotion represents a powerful tool for analysing pedestrian movement and evacuation dynamics at the scale of large public and transport environments. Its strengths lie in spatial realism, scalability, and integration with design workflows, making it particularly suitable for urban planning and infrastructure-focused safety assessments within the broader landscape of evacuation simulation tools. In safety applications, MassMotion is often used to analyse evacuation and crowd management strategies in transport hubs and large public venues, particularly under high-density or emergency conditions. From a safety perspective, MassMotion is most suitable for analysing evacuation and crowd management problems in large-scale public and transport environments, especially where high-density movement and operational scenarios are critical.

4.3 BuildingEXODUS

BuildingEXODUS is a specialised evacuation simulation tool developed by the Fire Safety Engineering Group (FSEG) at the University of Greenwich and represents one of the most academically grounded evacuation models currently in use. Unlike commercially driven platforms primarily optimised for workflow efficiency and visualisation, buildingEXODUS has been developed with a strong emphasis on analytical precision, behavioural representation, and scientific validation, particularly in the context of fire safety engineering. Compared to other tools, buildingEXODUS incorporates a more detailed representation of behavioural and physiological factors, allowing agents to respond to environmental conditions and stressors in a more differentiated manner.

From a modelling perspective, buildingEXODUS employs an agent-based approach implemented within a discrete spatial framework. The environment is represented as a network of nodes and arcs, through which individual agents move according to rule-based decision logic. Each agent is characterised by a detailed set of attributes, including age, gender, mobility level, familiarity with the environment, and behavioural response parameters. This structure enables the modelling of heterogeneous populations and differentiated evacuation behaviour under emergency conditions [40].

A key strength of buildingEXODUS lies in its explicit consideration of physiological and environmental constraints. The model can account for the effects of smoke, heat, reduced visibility, and toxic exposure on walking speed, decision-

making, and survivability. Integration with fire models such as CFAST allows evacuation simulations to be conducted under dynamically evolving hazard conditions, supporting the assessment of Available Safe Egress Time (ASET) and Required Safe Egress Time (RSET) relationships.

BuildingEXODUS has been extensively applied in research and regulatory contexts, including evacuation studies of high-rise buildings, passenger ships, aircraft cabins, and transport terminals. Validation efforts have drawn on experimental data, evacuation drills, and real incident analyses, making buildingEXODUS one of the most empirically informed evacuation tools available [4, 41]. Its outputs are therefore frequently referenced in academic studies addressing evacuation dynamics and fire safety performance.

The software supports two- and three-dimensional visualisation; however, visual realism is not its primary focus. Compared to more visually oriented tools, the user interface of buildingEXODUS is relatively technical and requires specialised training. This complexity may limit its accessibility for non-expert users, but it also reflects the model's emphasis on analytical transparency and control over simulation parameters.

Limitations of buildingEXODUS include higher demands on data preparation and user expertise, as well as reduced suitability for large open urban environments where continuous-space modelling may be advantageous. Nevertheless, for research-oriented applications and detailed fire-integrated evacuation analysis, buildingEXODUS remains a reference tool that significantly contributes to the scientific foundation of evacuation modelling. In safety engineering, buildingEXODUS is commonly applied in fire safety analysis, including the evaluation of evacuation times and the interaction between occupant movement and hazardous conditions. In safety engineering practice, buildingEXODUS is particularly suited for detailed fire evacuation analysis, including scenarios where interaction between occupants and hazardous conditions must be explicitly modelled.

4.4 LEGION

LEGION is a pedestrian simulation and crowd analysis tool developed by Bentley Systems and is widely applied in the design and operational assessment of transportation infrastructure and high-occupancy public spaces. The software is particularly prevalent in projects involving railway stations, metro systems, airports, public squares, and large urban developments, where the primary focus lies on pedestrian flow, capacity analysis, and level-of-service evaluation [42].

LEGION is based on an ABM framework that represents pedestrian movement in continuous space. Agents navigate through the environment using empirically derived movement rules that govern acceleration, deceleration, obstacle avoidance, interpersonal spacing, and route choice. This continuous-space representation enables realistic simulation of pedestrian trajectories, including smooth turning behaviour, lane formation, and group movement patterns, which are critical in high-density transport environments.

A defining strength of LEGION lies in its strong integration with architectural and infrastructure design workflows. The software supports the import of BIM and CAD data in formats such as IFC and DWG and integrates seamlessly with platforms like Autodesk Revit and Bentley OpenBuildings Designer. This interoperability allows evacuation and

pedestrian flow analyses to be conducted in parallel with design development, supporting iterative optimisation of layouts, corridor widths, stair capacities, and access control elements.

LEGION provides a range of analytical outputs tailored to transport planning and crowd management, including pedestrian density heatmaps, travel time distributions, bottleneck identification, and performance indicators related to level of service. These outputs are particularly valuable for assessing operational conditions during peak demand periods and for evaluating the impact of design interventions on pedestrian safety and comfort.

The software has been applied in numerous large-scale infrastructure projects, including metro station upgrades, airport terminal expansions, and urban regeneration schemes. For example, LEGION has been used to optimise pedestrian circulation and reduce congestion at major transport hubs, contributing to improved evacuation performance and overall system resilience [43]. Behavioural representation in LEGION is based primarily on empirically derived movement rules, focusing on realistic pedestrian dynamics rather than explicit modelling of psychological or social processes.

Despite its strengths in pedestrian flow analysis, LEGION exhibits limitations when applied to evacuation scenarios involving complex hazard conditions. Native integration with fire and smoke simulation is limited, and behavioural modelling focuses primarily on movement efficiency rather than psychological responses to extreme stress. As a result, LEGION is most effective when used for capacity-driven evacuation assessments and as a complementary tool within broader safety engineering workflows.

Overall, LEGION represents a mature and reliable simulation platform for analysing pedestrian movement and evacuation dynamics in transport-oriented and urban public spaces. Its emphasis on empirical movement rules, continuous-space modelling, and BIM integration positions it as a key component of the state of the art in evacuation and crowd simulation, particularly for infrastructure-focused applications.

Compared to other tools, LEGION places stronger emphasis on empirically calibrated pedestrian movement and level-of-service metrics, which makes it particularly suitable for capacity-driven assessments rather than behaviourally complex evacuation scenarios. In practice, LEGION supports safety assessments related to crowd capacity, evacuation planning, and risk mitigation in transport infrastructure and large public spaces. LEGION is most suitable for safety problems related to crowd capacity, flow management, and evacuation planning in transport infrastructure and large public spaces.

4.5 FDS+Evac

FDS+Evac is an evacuation modelling framework developed by the National Institute of Standards and Technology (NIST) as an extension of the FDS. Unlike most evacuation tools that prioritise behavioural modelling and spatial navigation, FDS+Evac is fundamentally grounded in physical modelling, coupling evacuation dynamics with CFD simulations of fire, smoke, heat transfer, and toxic gas propagation [24, 44].

In FDS+Evac, evacuation is simulated through an agent-based module that operates within the same computational domain as the fire model. Agents represent individual

occupants and their movement is influenced directly by environmental conditions calculated by FDS, including reduced visibility, elevated temperatures, and exposure to toxic species. Walking speed, route choice, and survivability are dynamically adjusted in response to these hazard parameters, enabling a physically consistent representation of evacuation under fire conditions.

The principal strength of FDS+Evac lies in its ability to concurrently model hazard development and human response, making it particularly valuable for performance-based fire safety engineering, regulatory assessment, and research-oriented studies. The framework is frequently applied to analyse ASET, RSET, and their interaction under realistic fire scenarios in buildings such as shopping centres, offices, tunnels, and industrial facilities [45].

From a computational perspective, FDS+Evac is considerably more demanding than standalone evacuation tools. The need to resolve fluid dynamics at fine spatial and temporal scales results in high computational costs and longer simulation times. Geometry preparation and scenario definition typically require advanced technical expertise, and user interaction is less intuitive than in commercially oriented evacuation software. Visualisation of results is commonly performed using auxiliary tools such as Smokeview or external pre- and post-processing environments. In FDS+Evac, behaviour is largely constrained by physical conditions, with agent responses driven by environmental variables such as visibility, temperature, and toxic exposure rather than complex behavioural decision-making models.

Behavioural modelling in FDS+Evac is intentionally constrained to ensure consistency with the physical hazard model. While this enhances physical realism, it also limits the representation of complex psychological and social behaviours. As a result, FDS+Evac is most effective when used in combination with other evacuation tools or as part of a multi-method analysis framework that balances behavioural exploration with physical accuracy.

Despite these limitations, FDS+Evac occupies a unique position within the state of the art. Its strong scientific foundation, open research orientation, and close alignment with fire safety standards make it a benchmark tool for validating evacuation performance under hazardous conditions. In the broader ecosystem of evacuation simulation tools, FDS+Evac provides an essential reference for understanding the physical constraints and limits of human egress during fire emergencies.

In practical applications, FDS+Evac is often used in combination with other evacuation tools to complement its strong physical modelling with more flexible behavioural representations. FDS+Evac is extensively used in performance-based fire safety engineering to simulate evacuation under realistic fire conditions and to assess compliance with safety criteria such as ASET/RSET. FDS+Evac is most suitable for safety-critical fire scenarios requiring physically realistic simulation of fire dynamics and their impact on evacuation performance.

5. COMPARATIVE SYNTHESIS

To enhance the consistency and transparency of the comparison, the main characteristics of the analysed tools are summarised in Table 1, where all platforms are evaluated using the same set of criteria.

A comparative synthesis of evacuation simulation tools is essential for understanding their relative strengths, limitations, and suitability for different application contexts. Rather than identifying a universally superior solution, this synthesis emphasises how differences in modelling paradigms, computational assumptions, and intended use cases shape the performance and applicability of individual tools.

Across the analysed platforms, ABM emerges as the dominant approach, yet its implementation varies considerably. Pathfinder and MassMotion prioritise continuous-space navigation and user-oriented workflows, enabling efficient scenario testing and visual communication. In contrast, buildingEXODUS and FDS+Evac emphasise analytical precision and physical consistency, often at the expense of usability and computational efficiency. LEGION occupies an intermediate position, combining empirically derived movement rules with strong integration into infrastructure design processes.

Visualisation capabilities represent a key differentiating factor. Tools such as Pathfinder, MassMotion, and LEGION provide advanced three-dimensional visualisation and intuitive graphical interfaces that support stakeholder communication and iterative design. Conversely, buildingEXODUS and FDS+Evac focus primarily on analytical outputs, requiring greater expertise to interpret results but offering higher transparency regarding underlying model assumptions.

Integration with fire and environmental hazard modelling further distinguishes the tools. FDS+Evac offers the most comprehensive coupling of evacuation and fire dynamics, enabling physically realistic assessment of ASET/RSET relationships. Pathfinder and buildingEXODUS support indirect or partial integration with fire simulation tools, while MassMotion and LEGION are primarily oriented toward non-fire evacuation and pedestrian flow analysis. This distinction has significant implications for tool selection in performance-based fire safety engineering versus operational crowd management.

Calibration and validation remain critical challenges across all platforms. While some tools offer mechanisms for parameter tuning and sensitivity analysis, systematic validation against empirical evacuation data is limited. BuildingEXODUS and FDS+Evac benefit from closer ties to experimental research and regulatory frameworks, whereas commercially oriented tools often rely on practitioner expertise and scenario-based reasoning. This divergence underscores the need for standardized validation protocols and shared benchmark datasets.

From an application perspective, no single tool satisfies all requirements of evacuation analysis. Pathfinder is particularly effective for building-scale evacuation studies requiring strong visualisation and integration with fire modelling. MassMotion and LEGION excel in large-scale transport and urban environments where pedestrian flow dominates. BuildingEXODUS and FDS+Evac provide superior analytical depth for research-intensive and fire-critical scenarios. Tool selection should therefore be guided by project objectives, regulatory context, and available expertise rather than perceived technological sophistication.

Overall, the comparative synthesis confirms that evacuation simulation tools form a complementary ecosystem rather than a competitive hierarchy. Their combined use, informed by a clear understanding of methodological trade-offs, offers the greatest potential for robust and credible evacuation analysis.

6. DISCUSSION

The comparative review of evacuation simulation tools reveals a field that has reached a significant level of technical maturity, yet continues to face persistent methodological and conceptual challenges. While contemporary tools provide increasingly sophisticated representations of spatial environments and pedestrian movement, their scientific robustness and practical reliability remain constrained by limitations in behavioural modelling, empirical validation, and standardisation. From a safety engineering perspective, these tools play a critical role in analysing evacuation performance under defined risk scenarios, supporting both design optimisation and regulatory decision-making. The following discussion is structured in relation to the research questions defined in the Introduction, in order to explicitly link the findings of the review to the analytical framework of the study.

One of the most salient findings of this review is the inherent trade-off between usability and analytical depth. Commercially oriented tools such as Pathfinder, MassMotion, and LEGION prioritise intuitive interfaces, three-dimensional visualisation, and seamless integration with design workflows. These characteristics facilitate widespread adoption in professional practice and support communication with non-technical stakeholders. However, this emphasis on usability often entails simplified behavioural assumptions and limited transparency regarding underlying model logic. In contrast, research-oriented tools such as buildingEXODUS and FDS+Evac provide greater control over modelling parameters and closer alignment with physical and experimental data, but require substantial expertise and computational resources.

Behavioural realism emerges as a central unresolved issue across all reviewed tools. Despite extensive evidence that evacuation outcomes are strongly influenced by psychological stress, social attachment, leadership, and group dynamics, most simulations continue to represent behaviour through simplified rule-based mechanisms. Vulnerable populations are frequently reduced to modified movement speeds rather than being modelled as socially embedded actors with specific assistance needs [46]. This gap between empirical behavioural research and computational implementation limits the predictive validity of evacuation simulations, particularly in extreme or non-standard scenarios.

Validation represents another critical challenge. The review confirms that systematic empirical validation of evacuation models remains scarce, primarily due to the limited availability of high-quality evacuation data. While experimental studies, drills, and post-incident analyses provide valuable insights, they are difficult to generalise and often constrained by ethical, logistical, and safety considerations. As a result, many evacuation simulations rely on expert judgement and sensitivity analysis rather than rigorous validation, which complicates their use in regulatory and policy contexts.

The increasing integration of evacuation simulation with digital twins, intelligent sensors, and artificial intelligence offers promising opportunities to address some of these limitations. Real-time data acquisition and adaptive modelling could significantly enhance situational awareness and support dynamic evacuation guidance. However, these advances also introduce new challenges related to data quality, privacy, interoperability, and algorithmic transparency. Without clear methodological standards, the growing complexity of evacuation systems risks obscuring rather than improving

decision-making.

From a policy and institutional perspective, the review highlights a persistent gap between technological capability and formal adoption. Although evacuation simulations are widely used in design and consultancy practice, their legal and normative status remains ambiguous in many jurisdictions. The absence of standardised guidelines for model selection, calibration, and interpretation limits their acceptance as authoritative evidence in safety assessments and approval processes.

Overall, the discussion underscores that evacuation simulation tools should be understood as decision-support instruments rather than deterministic predictors. Their value lies in comparative scenario analysis, identification of vulnerabilities, and exploration of design alternatives. To fully realise this potential, future research and practice must prioritise methodological transparency, empirical grounding, and interdisciplinary collaboration.

In relation to the research questions, the main findings can be summarised as follows:

RQ1: Contemporary evacuation simulation is dominated by ABM, often complemented by CA and hybrid approaches, with increasing integration of physical and data-driven components.

RQ2: The analysed tools exhibit distinct strengths and limitations, particularly in terms of trade-offs between usability, behavioural realism, and integration with hazard modelling, confirming that tool selection is context-dependent.

RQ3: Key methodological challenges include limited behavioural realism, insufficient empirical validation, and lack of standardisation, all of which constrain the reliability and comparability of simulation outcomes.

RQ4: Future development directions include improved behavioural modelling, integration with real-time data sources, development of validation frameworks, and stronger institutional and regulatory embedding.

7. RESEARCH GAPS AND FUTURE DIRECTIONS

The state-of-the-art review presented in this paper reveals several persistent research gaps that limit the scientific robustness, interoperability, and broader institutional adoption of evacuation simulation tools. Addressing these gaps is essential for advancing evacuation modelling from a predominantly scenario-based analytical practice toward a more empirically grounded and standardised scientific discipline.

A fundamental research gap concerns the empirical validation of evacuation models. Despite decades of development, there is still a lack of shared, high-quality datasets derived from real-world evacuations, large-scale drills, or controlled experiments. Ethical constraints, safety considerations, and logistical challenges severely limit the availability of such data. As a result, validation efforts remain fragmented and tool-specific, hindering meaningful cross-comparison and cumulative scientific progress. Future research should prioritise the development of anonymised benchmark datasets and standardised validation protocols that enable systematic evaluation of evacuation models across different environments and population profiles.

Behavioural modelling represents a second critical gap. While empirical studies consistently demonstrate the influence

of psychological stress, social attachment, leadership, and group behaviour on evacuation outcomes, these factors are only partially reflected in current simulation tools. Vulnerable populations, including elderly individuals, children, and persons with disabilities, are often modelled through simplified mobility parameters rather than through socially and cognitively informed behavioural representations. Advancing behavioural realism will require closer integration of insights from psychology, sociology, and human factors research, as well as the incorporation of data derived from virtual reality experiments and observational studies.

Standardisation and interoperability constitute another major challenge. Evacuation simulation tools currently rely on heterogeneous data structures, modelling assumptions, and output formats, which limits reproducibility and hampers integration with other safety engineering systems. The absence of open standards for model exchange and documentation also constrains collaboration between research groups and practitioners. Future efforts should focus on developing common data schemas, open application programming interfaces, and transparent reporting guidelines that facilitate interoperability and methodological transparency.

The increasing integration of evacuation simulation with digital twins, sensor networks, and artificial intelligence introduces both opportunities and unresolved questions. While real-time data integration and adaptive modelling hold promise for improving situational awareness and decision support, they also raise concerns related to data quality, algorithmic bias, privacy protection, and explainability. Research is needed to establish robust methodological frameworks that balance innovation with reliability, ethical considerations, and regulatory compliance.

Finally, the institutional and regulatory embedding of evacuation simulation remains underdeveloped. Although simulations are widely used in professional practice, their role in formal approval processes and safety regulations is often ambiguous. Clear methodological guidance is lacking regarding acceptable modelling assumptions, calibration requirements, and interpretation of results. Future work should therefore address not only technical and scientific challenges, but also the translation of evacuation simulation research into standards, guidelines, and educational curricula that support consistent and responsible application.

Collectively, these research gaps highlight the need for interdisciplinary collaboration and coordinated international efforts. By addressing validation, behavioural realism, standardisation, and institutional integration in a systematic manner, evacuation simulation research can evolve toward more credible, transparent, and impactful contributions to public safety.

8. CONCLUSIONS

These conclusions directly address the research questions defined at the beginning of the paper. This paper has presented a comprehensive state-of-the-art review of evacuation simulation tools used for risk analysis and safety planning in public and urban environments. By systematically synthesising modelling paradigms, software platforms, and applied practices, the review clarifies the current landscape of evacuation simulation and addresses long-standing fragmentation in both research and professional application.

The analysis demonstrates that contemporary evacuation

simulation tools are predominantly based on ABM, often complemented by CA, hybrid formulations, and, in selected cases, physically coupled fire and smoke simulations. While tools such as Pathfinder, MassMotion, LEGION, buildingEXODUS, and FDS+Evac differ significantly in scope, usability, and analytical depth, none can be regarded as universally optimal. Instead, each platform occupies a distinct position within a complementary ecosystem of tools tailored to specific objectives, environments, and regulatory contexts.

A central contribution of this review lies in its critical examination of methodological limitations. Persistent challenges related to behavioural realism, empirical validation, and standardisation constrain the predictive reliability and institutional acceptance of evacuation simulations. These limitations underscore the need to interpret simulation outputs as decision-support evidence rather than deterministic predictions, particularly when used to inform high-stakes safety decisions.

Based on the comparative analysis, several specific takeaways can be identified:

(i) no single tool provides a comprehensive solution, and tool selection is inherently context-dependent;

(ii) a clear trade-off exists between usability and analytical depth, with commercially oriented tools prioritising accessibility and research-oriented tools offering greater physical and behavioural fidelity;

(iii) integration with fire and environmental hazard modelling represents a key differentiating factor, particularly in performance-based safety engineering;

(iv) behavioural modelling remains simplified across most tools and constitutes a major limitation affecting predictive validity; and

(v) the lack of standardised validation frameworks limits cross-tool comparability and broader institutional adoption.

The review further highlights the transformative potential of emerging technologies, including digital twins, artificial intelligence, sensor networks, and edge computing. When integrated within robust methodological frameworks, these technologies offer promising avenues for enhancing situational awareness, adaptive evacuation guidance, and data-driven model calibration. However, their effective deployment requires careful attention to transparency, ethical considerations, and regulatory alignment.

From a scientific perspective, this paper advances the field by explicitly identifying research gaps and articulating future directions that extend beyond isolated case studies and tool descriptions. From a practical and policy-oriented standpoint, the findings emphasise the importance of clear guidelines, interdisciplinary collaboration, and education to support responsible and consistent use of evacuation simulation in safety engineering and public space planning.

From a safety engineering perspective, the findings of this review have several practical implications. First, the selection of evacuation simulation tools should be explicitly aligned with the type of risk scenario under consideration, such as building fires, transport infrastructure incidents, or mass gatherings. Second, practitioners should be aware of the trade-offs between usability and analytical depth, particularly when simulations are used for regulatory or design purposes. Third, the limited representation of human behaviour and the lack of standardised validation highlight the need for cautious interpretation of simulation outputs in safety-critical decision-making. Finally, the results support the increasing role of evacuation simulation in performance-based safety

engineering, where it serves as a key tool for evaluating evacuation effectiveness and supporting compliance with safety requirements.

In conclusion, evacuation simulation represents a mature yet evolving domain at the intersection of modelling science, human behaviour research, and safety policy. Continued progress will depend on coordinated efforts to strengthen empirical foundations, improve behavioural representation, and embed simulation methodologies within transparent institutional frameworks. When these conditions are met, evacuation simulation tools can play a decisive role in enhancing the resilience and safety of public environments and in supporting evidence-based safety engineering practice.

These findings emphasise that evacuation simulation should be applied as a decision-support tool, requiring careful interpretation within its methodological limitations. Their primary value lies in supporting safety engineering applications, particularly in the evaluation of evacuation scenarios, risk mitigation strategies, and performance-based design.

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