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The critical role of simulation and modeling in fire evacuation: An examination of research trends

Yangın tahliyesinde simülasyon ve modellemenin kritirik rolü: Araştırma trendlerinin incelenmesi

Betül ULU[1], Deniz Efendioğlu[1]*

[1]Institute of Science, Ankara Yildirim Beyazit University, Ankara, Türkiye.
betulkali@gmail.com, defendioglu@aybu.edu.tr

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Abstract

Fire evacuation planning is crucial in high-risk environments like high-rise buildings and underground facilities. Ensuring proper safety measures is vital for minimizing risks and ensuring occupant safety. Simulation models have become essential tools for evaluating and optimizing evacuation processes. They enable scenario testing, helping identify potential risks and develop effective evacuation plans. Additionally, simulation models provide a low-cost, time-efficient, and risk-free experimental environment, making realistic scenario testing possible without real-world dangers. This study systematically reviewed 75 research articles published over the last 15 years to analyze fire evacuation research trends. A bibliometric analysis using the electronic database was conducted, examining publication trends by year, category, and country. The analysis revealed that research is dominated by modern technologies for evacuation training, such as virtual simulations and agent-based models, which reduce costs and minimize operational disruptions compared to traditional evacuation drills. Following this analysis, the study identified that research trends are primarily focused on high-rise buildings and underground facilities, where evacuation is challenging due to structural complexity and high occupant density. This study highlights the role of modern technologies in fire evacuation and offers insights for improving safety measures and evacuation protocols in complex structures. The findings aim to guide researchers, engineers, and policymakers in enhancing fire safety and emergency preparedness.

Keywords: Fire evacuation, Simulation, Modeling, High-rise building, Underground facilities.

Öz

Yangın tahliye planlaması, yüksek katlı binalar ve yer altı tesisleri gibi yüksek riskli ortamlarda kritik bir öneme sahiptir. Bu tür yapılarda doğru güvenlik önlemlerinin uygulanması, riskleri en aza indirmek ve bina sakinlerinin güvenliğini sağlamak açısından hayati önemdedir. Simülasyon modelleri, tahliye süreçlerini değerlendirmek ve optimize etmek için vazgeçilmez araçlar haline gelmiştir. Bu modeller, farklı senaryoların test edilmesine olanak tanıyarak potansiyel risklerin belirlenmesine ve etkili tahliye planlarının geliştirilmesine yardımcı olmaktadır. Ayrıca, simülasyon modelleri düşük maliyetli, zaman açısından verimli ve risksiz bir deneysel ortam sunarak gerçek tehlikeler olmadan gerçekçi senaryo testlerinin yapılmasını mümkün kılmaktadır. Bu çalışmada, son 15 yılda yayınlanmış 75 bilimsel makale sistematik olarak incelenerek yangın tahliyesine yönelik araştırma eğilimleri analiz edilmiştir. Elektronik veri tabanı kullanılarak yapılan bibliyometrik analizde literatür, yayın yılı, kategori ve ülke bazında değerlendirilmiştir. Analiz sonuçları, literatürün büyük ölçüde sanal simülasyonlar ve ajan tabanlı modeller gibi modern teknolojilerle yürütülen tahliye eğitimi araştırmaları tarafından domine edildiğini ortaya koymuştur. Bu teknolojiler, geleneksel tahliye tatbikatlarına kıyasla maliyetleri düşürmekte ve operasyonel kesintileri en aza indirmektedir. Yapılan bu analiz doğrultusunda, araştırma eğilimlerinin büyük ölçüde yüksek katlı binalar ve yer altı tesislerine odaklandığı belirlenmiştir; bu tür ortamlarda tahliye, yapısal karmaşıklık ve yüksek nüfus yoğunluğu nedeniyle zorlu bir süreçtir. Bu çalışma, yangın tahliyesinde modern teknolojilerin önemini vurgulamakta ve karmaşık yapılar için daha etkili güvenlik önlemleri ile tahliye protokollerinin geliştirilmesine yönelik değerli bilgiler sunmaktadır. Bulgular, yangın güvenliği ve acil durum hazırlıklarının iyileştirilmesi için araştırmacılara, mühendisler ile politika yapıcılara rehberlik etmeyi amaçlamaktadır.

Anahtar kelimeler: Yangın tahliyesi, Simülasyon, Modelleme, Yüksek binalar, Yeraltı tesisleri

1 Introduction

Fire protection is highly complex and requires significant responsibility, as it involves safeguarding both human lives and property. Various factors, such as the increase in the world's population and the advancement of science, technology, and industry, have reinforced the importance of fire protection. This discipline, as old as the discovery of fire itself, has evolved throughout history in parallel with the scientific and technological advancements of human society [1].

The historical evolution of the fire protection discipline has not been limited to the prevention and extinguishing of fires; it has also encompassed the development of strategies aimed at the safe evacuation of people. Providing safe and easy evacuation routes during a fire is one of the most critical elements, as fast and effective evacuation is essential for preventing loss of life [2]. Consequently, with advancements in science and technology, modern methods have begun to be applied in fire safety. Evacuation modeling and simulation are among these modern methods used in fire protection.

In the past decade, significant progress has been made in evacuation models used in fire safety. Initially, these tools modeled human movement using simple calculations. Today, they have evolved into advanced systems capable of simulating

*Corresponding author/Yazışılan Yazar

complex behaviors and incorporating agent-based approaches to reflect decision-making processes [3].

The critical aspects of modeling and simulation in fire safety can be summarized as follows:

- Low Cost and Time Efficiency: Compared to the financial and organizational challenges of traditional fire evacuation drills, modeling and simulation offer low-cost, time-independent virtual tests, accelerating the design process and reducing costs.
- Risk-Free Experimental Environment: Modeling and simulation allow for the analysis of scenarios that are difficult or risky to test in real life, contributing to the development of safer evacuation routes and strategies.
- Innovation and Diverse Scenarios: By enabling various experiments and scenarios, they facilitate the planning of pedestrian flow in densely populated areas during emergencies and help anticipate potential problems.
- Safe Route Planning: Modeling and simulation make it easier to create safe routes by considering many factors in the evacuation of complex buildings. Evacuation routes not only ensure that people leave the building as quickly as possible but also minimize panic, congestion, and bottlenecks.
- Analytical and Data-Driven Approach: The data obtained from fire evacuation modeling can be used to optimize evacuation processes and improve safety standards.
- Flexibility: Models can be adapted to different building types and usage scenarios, aiding in the development of fire safety solutions and the emergence of innovative designs.
- Management of Complex Systems: Modeling can simultaneously address multiple factors such as human behavior, building design, and fire spread dynamics in the creation of evacuation plans. It allows for more accurate and detailed representations of complex systems, including dynamics, interactions, and behaviors that are difficult to observe and analyze directly [4]

This study aims to demonstrate that modeling and simulation techniques are critical tools in fire evacuation processes by analyzing existing research trends in the literature, identifying the areas where these techniques are predominantly applied, and contributing to future directions in simulation and modeling.

This study contributes to the existing literature by providing a comprehensive overview of simulation-based approaches to evacuation modeling, identifying key developments and persistent gaps. By examining studies that utilize simulation tools for evacuation modeling, this research identifies prevailing trends, methodological approaches, and critical application areas. It maps the evolution of simulation-based evacuation research, highlights gaps in the existing literature, and provides a roadmap for future work. The findings emphasize the growing use of modern simulation tools in improving evacuation efficiency and informing safety strategies. Through thematic and bibliometric analysis, the study offers insights that can guide researchers and practitioners in developing more effective and context-specific fire evacuation models. The research flow is as follows:

In the first section, the importance of simulation and modeling in fire protection is emphasized, and fire statistics are reviewed. The second section explains the methodology, including the research questions and the steps followed. The third section provides an overview of studies in the literature, focusing on high-rise building and tunnel fires, and highlights key observations. The fourth section summarizes the main findings of the review. Finally, the fifth section discusses the study's contributions to the existing literature.

Fire statistics provide critical information for fire safety and risk management. These statistics enable the analysis of the frequency, location, causes, and impacts of fire incidents. With the data obtained, fire prevention strategies can be developed, risk assessments can be conducted, and resources can be allocated more effectively. Additionally, historical data can guide the implementation of necessary measures to prevent similar incidents in the future. Global fire statistics are published by CTIF (International Association of Fire and Rescue Services), which reports fire data from approximately seventy countries annually. However, Turkey is not included among the countries covered in these reports [5]. The most recent edition of the CTIF World Fire Statistics Report, published in 2024 and containing data from the year 2022 contains various data, including total fire statistics by country, reasons for fire service calls, distribution of fire types (building fires, vehicle fires, forest fires, waste fires, etc.), and the distribution of fire-related deaths and injuries by fire type.

Table 1 below presents the total distribution of fires in participating countries worldwide according to CTIF statistical reports for the years 2013–2022. Although the number of participating countries varies, the data indicate a general increase in the number of fires over the years. When examining fire-related death rates, it is observed that the rates have remained relatively stable over time, suggesting that fire safety measures have been effective [6].

Table 2 presents the distribution of fire-related deaths by type of fire in certain countries participating in the CTIF fire statistics report for the year 2022. Population refers to the total population of each country, given in thousands. Fire deaths indicate the number of people who died due to fire incidents in each country. The table includes the percentage of fire-related deaths for each country, categorized into residential buildings, other structures, vehicles, and others (unspecified areas). This type of distribution is crucial for analyzing the effectiveness of fire safety policies in different countries and identifying which types of fires result in higher fatalities. The table indicates that residential fires dominate fire-related death rates, highlighting the need to enhance preventive measures against such fires. The high percentage of the "Other" category in some countries suggests the need for more detailed data collection and improvements in the classification of fire types.

Table 1. Total distribution of fires in world countries between 2013 and 2022.

Year	Number of countries	Total population (billion)	Number of fires (million)	Fire deaths (thousand)	Fires per 1,000 people	Fire deaths per 100,000 people	Average number of deaths per fire
2013	44	4.3	5.3	43.3	1.2	1	0.8
2014	45	4.3	5.4	42.9	1.2	1	0.8
2015	46	4.4	5.5	42.7	1.3	1	0.8
2016	47	4.5	5.4	42.7	1.2	1	0.8
2017	47	4.6	5.4	44.7	1.2	1	0.8
2018	49	4.8	5.5	43.6	1.2	0.9	0.8
2019	50	4.8	5.6	44	1.2	0.9	0.8
2020	52	4.9	5.4	41.1	1.1	0.8	0.8
2021	54	5.1	5.3	42.5	1	0.8	0.8
2022	55	5.2	5.1	40.8	1	0.8	0.8

Table 2. Distribution of fire-related deaths by type of fire in certain countries in 2022.

No	Country	Population (thousand)	Fire deaths	% Residential buildings	% Other buildings	% Vehicles	% Other
1	USA	333.271	2760	72.8	4.0	3.0	18.5
2	Russia	146.781	6976	58.0	2.6	1.4	38.1
3	Vietnam	100	247	73.3	2.8	1.2	22.7
4	Spain	47.486	176	74.4	3.3	1.1	22.2
5	Ukraine	41.168	1502	63.8	3.2	2.2	30.8
6	Poland	37.748	476	53.6	6.1	1.6	38.7
7	Kazakhstan	19.227	640	61.4	2.5	1.6	34.5
8	Belgium	11.559	82	82.9	4.9	1.2	11.0
9	Czechia	10.526	138	59.4	7.2	0.7	32.6
10	Greece	10.295	51	66.7	3.9	0.0	29.4

2 Methodology

This study adopts systematic literature review methodology to analyze research trends in fire evacuation modeling and simulation. The primary aim is to identify key areas where modeling and simulation techniques are predominantly applied and to contribute to future research directions. The methodology involves the following steps:

- Determination of the research questions,
- Planning the search process,
- Data Collection,
- Data Analysis.

Detailed information regarding these steps is provided below.

Research questions

In our systematic study, four research questions were identified and examined through eight inquiry points. Research questions are fundamental queries that guide the investigation of a specific topic during a research or review process. These questions enable researchers to access appropriate sources, help them determine suitable data collection methods, and provide the necessary information to answer the research questions.

Research questions (RQ) assist in defining, guiding, and organizing the scope of the research process. Additionally, through these questions, researchers can identify gaps in the research field and determine which resources are needed to fill those gaps. Therefore, research questions have a significant impact on the quality and effectiveness of the research. Below are the research questions and the steps taken in our study and Figure 1 presents the flow of the research questions in our study, illustrating their progression and structure.

RQ1: What are the key trends and characteristics of academic publications on fire evacuation?

1. The Web of Science (WOS) database was used for data collection.
2. Initially, sources related to fire evacuation were searched comprehensively and reliably for the period from 2010 to 2025.
3. Academic publications in the "All Fields" category with the title "Fire Evacuation" were reviewed.
4. The distribution of academic publications was analyzed according to WOS categories and countries.

RQ2: What are the main keywords used in fire evacuation research?

5. Keywords used in these academic publications were identified using VOSviewer.

RQ3: What is the scope of simulation use and the most prominent research trends in fire evacuation studies?

6. "Fire Evacuation" was searched in all fields, and the keyword "Simulation" was added.
7. Prominent research trends were identified, focusing on “High-rise buildings” and “Tunnel fires”.

RQ4: What are the key findings in fire evacuation research focused on high-rise buildings and tunnel fires?

8. Data from 75 selected articles were tabulated, and the results were discussed.

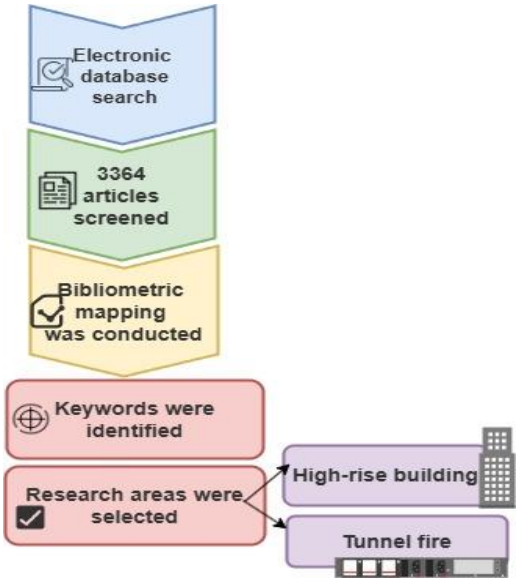

Figure 1. Flow of the research questions.

Planning the search process

In this step, a bibliometric analysis was conducted using the Web of Science (WOS) database. Based on the results, a systematic literature review was carried out focusing on high-rise building and tunnel fire evacuation studies. Articles published within the last 15 years (2010–2024) were included to ensure that the study incorporates recent developments and trends.

Data collection

The search aimed to specifically gather studies involving simulation or modeling techniques in fire evacuation contexts. To ensure the relevance and quality of the collected data, only peer-reviewed articles directly related to fire evacuation and using simulation or modeling techniques were included. In this step, searches were conducted in the Web of Science (WOS) database using the keywords "high rise building fire evacuation simulation" and "metro fire evacuation simulation", resulting in a total of 136 studies (75 on high-rise buildings and 61 on tunnel/ metro stations). Studies that were:

- Not directly related to fire evacuation, modeling or traditional evacuation methods,
- Without full-text access or written in languages other than English and Turkish,
- Duplicate or redundant publications,

were excluded. From the remaining studies, 34 articles on high-rise buildings and 41 articles on metro stations were selected for detailed analysis.

Data Analysis

The selected articles were analyzed based on key parameters, including:

- Research Focus: High-rise buildings, underground (tunnel/metro stations) facilities,
- Simulation Tools Used: Various simulation tools were used in the studies, including Pathfinder, AnyLogic, and FDS+Evac.
- Key Findings: Critical observations regarding evacuation strategies, safety improvements, and technological advancements.

The results were categorized and visualized to highlight research trends in fire evacuation modeling and simulation. Special attention was given to high-rise buildings and underground metro stations, which were identified as key focus areas. Gaps in existing research were noted, and potential directions for future studies were suggested.

3 Literature review

The purpose of the fire simulation literature review is to provide a comprehensive understanding of fire risk assessment methodologies and applications, as well as to analyze the inclusion of fire protection in engineering curricula[7]. These reviews aim to identify gaps in knowledge and practice, propose future research directions, and suggest improvements in fire safety.

High-rise building and tunnel station fires are particularly challenging due to their complex structures, high occupant loads, and prolonged evacuation times.

Fire incidents in underground metro stations are highly hazardous and complex events that require rapid and effective response. The dangers that may arise during a fire demand a swift evacuation process and well-coordinated intervention. Additionally, unlike other types of buildings, evacuation in such environments involves upward movement and unique architectural features, which necessitates a different approach. Therefore, a comprehensive fire safety plan is essential for underground metro stations. The 41 studies from the literature focusing on underground metro stations were tabulated. The table provides a detailed overview of key aspects of fire evacuation studies, including their objectives, case study scenarios, simulation tools, evaluation metrics, and key findings.

- Study Objective: Indicates the purpose of the study and outlines proposed solutions to the problem or situation being examined.
- Case Study Scenario: Describes the specific situation or conditions under which the simulation or model was tested.
- Simulation Tools: Specifies the software or simulation tools used and their role in the evacuation process.
- Evaluation Metrics: Lists the criteria used to evaluate the study, such as evacuation time, capacity, or safety improvements.
- Key Findings: Summarizes the significant results of the study and provides practical recommendations based on these findings. Simulation-based research on tunnel/metro stations is presented in Table 3.

Table 3. Simulation-based research on tunnel/ metro station evacuation

Paper	Study objective	Case study scenario	Simulation tools	Evacuation metrics	Key findings
[8]	Analyze the impact of various factors on passenger behavior during fire evacuation in metro stations.	Fire evacuation in a metro station	Cellular Automata Model	Evacuation capacity, station layout rationality	Station facilities redesign and layout improvements can enhance evacuation efficiency.
[9]	Enhance evacuation capacity in a complex metro transfer station.	Emergency evacuation in a transfer station	AnyLogic	Evacuation time, channel simulation time	Evacuation time can be reduced with improved evacuation methods, enhancing operators' emergency response.
[10]	Optimize metro station hall design to improve passenger flow and reduce congestion.	Passenger flow in metro station halls	AnyLogic	Regional density, average flow speed, time distribution	Design optimization reduces congestion and ensures smoother passenger movement, improving hall efficiency.
[11]	Optimize transfer subway station designed to alleviate crowding.	Transfer subway station reconstruction	AnyLogic	Evaluation index system (AHP method)	Widening staircases is the best solution for reducing crowding. Rounded corners and staircase-only areas are recommended for new designs.
[12]	Simulate and optimize passenger flow lines in railway stations to improve management efficiency.	Passenger flows in Lanzhou West Railway Station	AnyLogic	Security processing time, entrance flow proportion	Increasing security channels shortens processing time, and balancing passenger flow among entrances improves efficiency.
[13]	Optimize and simulate passenger transfer flow at Lanzhou West Center to improve transportation capacity.	Passenger transfer at Lanzhou West metro and high-speed train stations	AnyLogic	Bottleneck points, congestion, and queue waiting time	Proposed optimization strategies reduce congestion and waiting times effectively, enhancing transfer efficiency.
[14]	Analyze and optimize evacuation facility parameters to improve personnel evacuation during subway train fires in tunnels.	Subway train fire in tunnels	Cellular Automata Model, RNG turbulence model	Total evacuation time, exit congestion time	Optimization of evacuation facility parameters reduced total evacuation time by 72% and congestion time by 85%, with critical influence from walkway widths and bypass spacing.
[15]	Compare metro tunnel evacuation strategies: internal wind vs. traditional station evacuation.	Emergency evacuation in a metro tunnel	FDS, Building EXODUS	Smoke diffusion range, evacuation performance	Internal wind evacuation is the most effective strategy when available. Stairs are bottlenecks, and the train travel stage affects evacuation strategy selection
[16]	Study fire smoke spread and evacuation in deep metro models to enhance safety evaluation.	Fire scenario in a deep-buried metro	FDS+Evac, STEPS	Smoke spread characteristics, evacuation performance	Real-time effect of fire smoke on evacuation was analyzed, enhancing subway fire safety evaluation accuracy.

Table 3. Simulation- based research on tunnel/ metro station evacuation.

Paper	Study objective	Case study scenario	Simulation tools	Evacuation metrics	Key findings
[17]	Develop and compare evacuation path planning models to optimize evacuation efficiency at subway stations.	Evacuation at a subway station	Social Force Model (SFM), Fisk Stochastic User Equilibrium Model, Mass Motion	Total evacuation time, individual evacuation time, pedestrian distribution	Stochastic user equilibrium model reduces total evacuation time by 15% and balances pedestrian flow, preventing overcrowding. Closing exits and suspending escalators can significantly impact congestion and evacuation time.
[18]	Analyze evacuation efficiency under different fire scenarios and flow rates in subway stations.	Fire evacuation in a subway station	Path finder	Evacuation pressure, crowd control	Evacuation pressure is highest at stairway entrances. Exit width has little impact on evacuation pressure. Crowd control recommendations based on passenger numbers were provided.
[19]	Analyze the effect of fire on personnel evacuation in a platform transfer area using FDS+Evac simulation.	Fire evacuation in platform transfer area	FDS+Evac	Evacuation time, activity scope, route changes	Fire significantly affects evacuation by increasing time, limiting movement, and altering routes. Results guide underground space evacuation design.
[20]	Compare evacuation strategies for subway tunnel fires and evaluate the impact of tunnel length and emergency exit setup.	Subway tunnel fire in Nanjing Yangtze River Tunnel	FDS+Evac	Reaction time, action time, evacuation efficiency	Evacuation in place reduces reaction time but increases action time, while pulling the train into the station reduces total evacuation time. Tunnel length significantly affects evacuation strategy effectiveness.
[21]	Develop a real-time fire emergency evacuation simulation system for large infrastructures to improve evacuation efficiency and safety.	Fire evacuation in a busy subway station in China	BIM platform, FDS, evacuation simulation platform	Evacuation efficiency, route optimization	The proposed system increased evacuation efficiency by 12.87%, providing real-time dynamic optimal evacuation routes. Behavioral and psychological characteristics of evacuees were considered.
[22]	Analyze and simulate evacuation processes in a subway station under various disaster scenarios and multi-disaster coupling conditions.	Evacuation at Nanning Chaoyang Square subway under fire and flood scenarios.	AnyLogic	Evacuation time, number of evacuees	Fire and flood coupling scenarios significantly affect evacuation risk. Side A of the station hall floor posed the highest evacuation risk. Recommendations for evacuation strategies in multi-disaster scenarios were provided.
[23]	Analyze metro train fire evacuation reliability under smoke spread and propose strategies.	Passenger evacuation in metro train fire scenarios	Pathfinder	RSET, evacuation time, critical train position	RSET is affected by passenger load, seat arrangement, evacuation strategy, and train position. Critical point calculation effectively guides emergency evacuation strategies.
[24]	Conduct evacuation experiments in a large underground building to evaluate evacuation time and route selection in fire emergencies.	Fire evacuation at Guangzhou East Railway Station	EVACNET 4, composite occupant evacuation model	Evacuation time, route selection accuracy	Direct access to outdoor exits significantly reduces evacuation time. Experimental and simulation results were consistent, validating the models' accuracy and applicability.

Table 3. Simulation- based research on tunnel/ metro station evacuation.

Paper	Study objective	Case study scenario	Simulation tools	Evacuation metrics	Key findings
[25]	Simulate subway fire evacuation and assess parameter effects on evacuation time.	Fire evacuation at Haicang Avenue Subway Station	Pathfinder	Total evacuation time, crowd density, evacuation speed	Increased crowd dispersion requires longer evacuation time. Recommendations were made to optimize exit positions and increase exit width to improve evacuation efficiency.
[26]	Test and compare predictive capabilities of different evacuation modeling approaches and explore the influence of smoke and wayfinding on evacuation behavior.	Tunnel fire evacuation in Stockholm, Sweden	FDS+Evac, BuildingEXODUS, STEPS, Pathfinder, Gridflow, Simulex	Evacuation time, smoke impact, exit choice	FDS+Evac best represented the impact of smoke on walking speeds. Multi-model approach tested sensitivity and provided reliable comparisons. Models like Pathfinder and Simulex require external calibration for smoke effects.
[27]	Simulate evacuation process in a curved bi-directional tunnel during fire and analyze the influence of alarm systems on evacuation time.	Fire evacuation in a curved bi-directional Italian road tunnel	STEPS, CFD model	Evacuation time, pre-movement time	Walking time primarily influenced evacuation time. Alarm systems reduced evacuation time, improving safety for tunnel users.
[28]	Evaluate evacuation safety in a tunnel fire scenario using numerical simulations to analyze the effect of wind velocity and evacuee density on evacuation time.	Fire evacuation in a tunnel with varying ventilation conditions	FDS, Real-coded Cellular Automaton (RCA)	Evacuation time, wind velocity, evacuee density	Increased wind velocity and evacuee density prolong evacuation time. Numerical simulations provide a cost-effective method for evaluating tunnel ventilation changes.
[29]	Simulate fire scenarios in an urban tunnel with congested traffic and evaluate the impact of fire dynamics on evacuation safety.	Fire evacuation in Martwa Wisła tunnel, Gdansk	VISSIM, FDS, Pathfinder	Evacuation time, number of threatened people, fire detection time	Over half of the people trapped in the worst-case scenario may come into contact with life-threatening factors. Tunnel safety systems must support self-rescue efforts.
[30]	Develop an agent-based evacuation model for underground transport and identify key safety factors.	Underground transport emergency evacuation	AnyLogic	Evacuation time, critical safety factors	The proposed framework effectively evaluated critical factors like ticket gate type, walking speed, and group size, providing support for optimizing underground station design.
[31]	Analyze and evaluate the risk of fire evacuation in a subway station and propose improvement measures based on simulation results.	Fire evacuation at Wenze Road Station of Hangzhou Metro	AnyLogic	Risk level, evacuation delay time	Bottleneck areas such as stairs, gates, and passages pose higher risks. The proposed evaluation method is consistent with actual conditions and provides valuable reference for improving station evacuation safety.
[32]	Analyze safe evacuation strategies and processes for subway trains during fires.	Evacuation from a subway train under fire	Pathfinder, PyroSim	Evacuation time, passenger distribution, fire conditions	Provides insights into the effectiveness of different evacuation modes and highlights critical safety concerns, especially under extreme fire conditions.

Table 3. Simulation- based research on tunnel/ metro station evacuation.

Paper	Study objective	Case study scenario	Simulation tools	Evacuation metrics	Key findings
[33]	Develop a mathematical model to evaluate evacuation time and optimize evacuation routes during a fire in a road tunnel.	Fire evacuation in a road tunnel	Mathematical model, Pathfinder	Evacuation time, flow density, movement velocity, fire environment impact	The model closely matches Pathfinder results with a 0.77% error and provides effective recommendations for route optimization and crowd management.
[34]	Explore the feasibility of downward evacuation in deep-buried metro stations during a fire.	Fire in an underground metro station hall	Numerical method, FDS software	Smoke movement, temperature, CO concentration, visibility	Downward evacuation is feasible if the smoke exhaust system operates effectively.

Our study primarily focuses on simulation and modeling approaches; however, our literature review has revealed that various alternative evacuation methods have also been employed in other research. As an example of such studies;

- A solution is proposed for emergency evacuation in a non-symmetric metro station by utilizing Wireless Sensor Networks [44].
- A lightweight digital twin algorithm using Web3D technology and real-time data enhances metro station fire evacuation simulations by improving accuracy, efficiency, and dynamic visualization [45].
- The study proposes a VR-based online fire evacuation training system for metro stations, integrating VR technology with Building Information Modeling (BIM) and Fire Dynamics Simulator (FDS) data [46].
- Emergency evacuation in underground metro stations depends on understanding commuter exit choice behavior, analyzed through a choice experiment using SketchUp-3D models in Delhi metro stations[47].
- A new system is introduced to simulate 2D and 3D evacuation plans in fire incidents. This system helps people determine which direction to take for a safe evacuation during a fire [48].

It has been observed from these studies that modern technologies, particularly 3D simulation, play a significant role in evaluating metro fire evacuation scenarios. They can be utilized during the design phase to assess circulation and emergency evacuation issues in complex environments. However, the number of studies conducted on this subject in Turkey is limited [49]. Additionally, by simulating various scenarios, including different visibility conditions and passenger speeds, these tools can identify bottlenecks, assess station evacuation capacity, and enhance safety management in metro systems [50].

The evacuation of high-rise buildings during fires has become increasingly important with the rise of modern urbanization and population density. High-rise buildings are in greater demand because they require less space and can accommodate more people. However, ensuring safe and rapid evacuation from these buildings during a fire poses numerous risks. In high-rise fire situations, there are significant risks such as prolonged evacuation times, vertical fire spread, smoke and heat propagation, and the complexity of rescue operations. Therefore, carefully planning and implementing fire evacuation strategies in high-rise buildings is of vital importance. In our study, 34 articles focusing on high-rise buildings were tabulated from the literature. The study, similar to those conducted in underground metro stations, has been analyzed under the categories of Study Objective, Case Study Scenario, Simulation Tools, Evaluation Criteria, and Key Finding. Table 4 shows simulation-based search on high-rise buildings.

Table 4. Simulation- based research on high-rise buildings evacuation.

Paper	Study objective	Case study scenario	Simulation tools	Evacuation metrics	Key findings
[2]	Develop a methodology for accurate evacuation modeling and investigate evacuation behavior in high-rise buildings.	Evacuation in a high-rise office building in Istanbul	Building EXODUS	Evacuation time, death toll, sprinkler activation	Exit knowledge and occupant preferences significantly slow evacuation. Fires near the ground floor increase casualties, and failure in sprinkler systems leads to catastrophic outcomes.
[51]	Develop and evaluate optimal phased evacuation strategies to enhance safety during high-rise building fires.	Fire evacuation in a 25-story building with 2400 occupants.	Path finder, two-zone model, mathematical model	Staircase congestion time, smoke flow impact	Optimal phased evacuation cuts staircase congestion by 65%, highlighting the importance of smoke flow and pedestrian movement in planning.
[52]	Investigate the impact of various factors on evacuation time and validate evacuation models for tall buildings.	Evacuation experiments in a 107 m building, Bulgaria.	Path finder, real-life experiments	Evacuation duration, vertical speed	Real-life evacuations took 2-6 minutes, with simulations confirming results and full capacity evacuation taking 24:48 minutes. Regional data aids model validation, while recent years saw increased use of tools like Pathfinder, WayR, and EXODUS for accurate evacuation predictions.
[53]	Simulate and analyze fire-induced smoke movement and pressure distribution in high-rise building stairwells.	Fire-induced smoke movement in a high-rise stairwell	FDS	Airflow velocity, temperature distribution	Simulations showed a maximum deviation of 16.23% in airflow velocity and 12.3% in temperature. Pressure difference increases with height, but the presence of staircases causes non-monotonic pressure evolution. The turbulence model had a negligible impact on results.
[54]	Assess optimal egress strategies for total evacuation in high-rise buildings using egress models.	Evacuation in 50-floor twin towers with sky-bridges	Path finder, STEPS	Total evacuation time, strategy effectiveness	Seven strategies were tested; lowest times achieved with evacuation elevators and sky-bridges. Stairs and elevators without clear signage reduced effectiveness.
[55]	Develop and validate an agent-based egress framework for high-rise residences.	Fire evacuation in a high-rise residential building	Path finder, BIM model	Evacuation time, framework validation	Smartphone-based instructions cut evacuation time by 13-15 minutes. The egress framework using BIM, sensors, and smartphones improved safety, with occupant training recommended.
[56]	Simulate fire scenarios and develop optimal evacuation strategies for high-rise buildings.	Fire evacuation in the Yangtze River International Conference Center	Pyrosim, Path finder	T_{ASET}, T_{RSET}, Evacuation strategy effectiveness T_{ASET}: Available T_{RSET}: Necessary evacuation time	Comprehensive strategies cut TRSET by 79.6%. Optimal plans used elevator-refuge floors at night and staged batch evacuation during work hours, avoiding major congestion.
[57]	Assess evacuation performance in corridor-type high-rise buildings and develop an enhanced evaluation framework	Fire evacuation in a corridor types high-rise building	Building EXODUS, AHP-TOPSIS analysis	Evacuation time, performance assessment accuracy	Evacuation times in corridor buildings were 25%-34% shorter than in conventional high-rises. Layered evacuation reduced time by 9.7%. Night evacuations took 29.4% longer. An improved framework for corridor buildings was proposed.

Table 4. Simulation- based research on high-rise buildings evacuation.

Paper	Study objective	Case study scenario	Simulation tools	Evacuation metrics	Key findings
[58]	Analyze fire risk in high-rise buildings and assess evacuation performance under various structural conditions.	Fire evacuation in a high-rise building	CFAST, Building EXODUS	Smoke spread, CO concentration, evacuation time	The chimney effect accelerates smoke spread, raising suffocation risk. Sprinklers, smoke extraction, and proper stairwell door management extend evacuation time. Scissor staircases and guided evacuations boost efficiency.
[59]	Assess the building layout impact on evacuation and propose route improvements.	Fire evacuation in high-rise buildings	Graph Theory, Virtual Reality, eye-tracking	Evacuation time, attention allocation	Evacuation efficiency is significantly influenced by route characteristics and signage visibility. The study offers a comprehensive evaluation framework combining graph theory and VR, emphasizing the importance of spatial design and wayfinding in evacuation.
[60]	Assess the reliability of occupant evacuation in building fires using reliability analysis and sensitivity testing.	Fire evacuation in high-rise buildings	Reliability analysis, sensitivity analysis	Reliability probability index, pre-movement time sensitivity	Pre-movement time had the highest sensitivity (0.419) among all parameters, making it critical in evacuation modeling.
[61]	Assess the use of elevators for people with mobility limitations and propose a nudge-based phased evacuation strategy.	Fire evacuation in a 50-story high-rise building	Virtual Reality Path finder	Wait time reduction, safe elevator usage	Phased evacuation reduces wait time and ensures safer elevator use for those with mobility limitations
[62]	Simulate firefighting and rescue operations in complex high-rise buildings using GIS and BIM integration.	Fire incident simulation in Plasco multi-story building	BIM, GIS	Path length, safety of evacuation routes	In 87% of cases, safest paths were longer than shortest ones. Fifteen scenarios guided rescue operations using BIM and GIS models to find optimal fire evacuation paths.
[63]	Simulate and optimize fire evacuation in a university building complex with high occupant density.	Fire evacuation in a university building	BIM, Path finder	Evacuation time, congestion at safety exits	Lunch evacuations took longest due to student dispersion, while night evacuations were quickest. The optimized plan cut evacuation time by 15%-20%. Regional path planning is advised based on usage patterns.
[64]	Develop an agent-based model for simulating fire evacuation in public buildings and optimizing evacuation plans.	Fire evacuation	GAMA Platform, GAML	Evacuation time, evacuation plan effectiveness	The agent-based model showed fire speed and evacuee traits greatly affect evacuation. It's adaptable for various commercial buildings, with future plans to add fuzzy logic for better decision-making.
[65]	Integrate BIM and Agent-Based Modeling (ABM) for emergency evacuation simulations, incorporating characteristics of buildings and users.	Fire evacuation in Istanbul Technical University	BIM, Agent-Based Model (ABM)	Evacuation time, agent behavior, route optimization	By integrating BIM and ABM, realistic simulations were performed where agents with varying characteristics evacuated the building. The study demonstrated that decision-makers could use these simulations for accurate decision-making and developing effective evacuation strategies.
[66]	Analyze computerized evacuation models and highlight engineering advantages in fire safety.	Fire evacuation	Pyrosim, FDS+Evac	Evacuation time, human behavior analysis	The study highlights integrating human behavior in evacuation models. FDS+Evac simulations demonstrated fire-crowd interaction, with future validation planned to use experimental data.

Table 4. Simulation- based research on high-rise buildings evacuation.

Paper	Study objective	Case study scenario	Simulation tools	Evacuation metrics	Key findings
[67]	Build an evacuation model for a medical pension building using the SFM and ABM on the AnyLogic platform.	Fire evacuation in a medical pension building	AnyLogic, SFM	Evacuation time, psychological parameters impact	The study demonstrated that evacuation time is longest when psychological parameters are lower under the same number of evacuees. The simulation results emphasize the significant influence of mental parameters on evacuation efficiency.
[68]	Evaluate the safety and risk of fire evacuation under scenarios where emergency exits are randomly obstructed.	Fire evacuation	AnyLogic, Monte Carlo analysis	Evacuation time, risk probability	The study found that even though the floorplan meets safety criteria, the risk of obstruction is high. Monte Carlo analysis indicated a 1% probability of obstruction for all three emergency exits. Recommendations include increasing the minimum number of emergency exits and reconfiguring the floorplan.
[69]	Evaluate the safety of occupants' evacuation in high-rise and super-high-rise buildings.	Fire evacuation in high-rise and super-high-rise buildings in Egypt	Pathfinder	Required safe evacuation time (RSET), staircase congestion	The study concluded that staircase design significantly impacts R_{SET} time. Using elevators and refuge areas as auxiliary evacuation methods may enhance safety. Technical requirements for the use of elevators and refuge areas were provided for emergency evacuation in these building types.
[70]	Estimate evacuation time and evaluate scenarios for a high-rise and extra-large building.	Fire evacuation in a 41-story high-rise building in Bangkok	Path finder	Evacuation time, occupant load, exit stair congestion	The study simulated four cases, showing that evacuation time ranges from 2321 to 2841.8 seconds depending on the fire scenario and stair availability. Congestion significantly increases when only one exit stair is available. Scenarios were evaluated based on NFPA 101 Life Safety Code.
[71]	Conduct a parametric study on evacuation strategies in fire-exposed high-rise buildings.	Fire evacuation in a 32-story high-rise office building	Path finder	Evacuation time, situational awareness impact	The study evaluated evacuation with and without situational awareness, showing that incorporating situational awareness reduced evacuation time by up to 24%. Key factors influencing evacuation time are stairway location and the floor where the fire starts.
[72]	Study the evacuation rules and analyze the effect of family group behavior on evacuation in high-rise residential buildings.	Fire evacuation in a 30-story high-rise building	Path finder	Evacuation time, crowd congestion time	Family group behavior slows evacuation by increasing congestion. Larger groups hinder faster individuals, and obstacles near stairwells affect efficiency based on their position.
[73]	Compare microscopic and macroscopic evacuation models for high-rise residential buildings.	Fire evacuation in a high-rise building	Path finder, Evacuationz	Evacuation time, tool calibration	The study compared Pathfinder and Evacuationz, highlighting that tool calibration boosts prediction accuracy. Using both tools enabled broader scenario analysis, including stair width, building size, and evacuee numbers.
[74]	Analyze evacuation scenarios for elderly and children in high-rise hotels.	Fire evacuation in a high-rise hotel with special groups	Path finder	Evacuation time, personnel pairing schemes	Simulations showed placing elderly and children on lower floors shortened evacuation time. Solo evacuation was fastest, followed by two-person and three-person groups. Findings aid strategy improvement.

Table 4. Simulation- based research on high-rise buildings evacuation.

Paper	Study objective	Case study scenario	Simulation tools	Evacuation metrics	Key findings
[75]	Analyze elevator-assisted egress in super-high-rise buildings during evacuations.	Spatial Grid Evacuation Model	Spatial Grid Evacuation Model	Evacuation time, elevator usage efficiency	Elevator-assisted evacuation can reduce the physical strain on evacuees and improve evacuation efficiency in super-high-rise buildings.
[76]	Develop and evaluate evacuation strategies for super high-rise commercial buildings during fires.	Fire evacuation	Pyrosim, Path finder	Fire parameters, evacuation time, personnel distribution	Coordinated use of stairs, elevators, and refuge floors improves evacuation efficiency. Organized nighttime evacuation significantly reduces required time compared to unorganized evacuation, providing practical guidance for minimizing fire-related casualties.
[77]	Study evacuation processes and influencing factors in ultra high-rise buildings.	Evacuation in stairwells of ultra high-rise buildings	AnyLogic SFM	Evacuation speed, personnel density, stair slope gradient	Corner and stair areas are critical for evacuation; factors such as stair gradient and personnel density significantly affect evacuation speed, and targeted recommendations are provided to improve evacuation efficiency.
[78]	Develop and evaluate an elevator-aided evacuation model for ultra high-rise buildings.	Evacuation in ultra high-rise buildings with over 40 storeys	Cellular Automata Modeling	Evacuation time, phased vs. total evacuation, refuge floor interval	Refuge floor interval design significantly impacts evacuation efficiency; combining fast elevators with stair evacuation optimizes the evacuation process.
[79]	Analyze the evacuation process and factors affecting evacuation time in high-rise buildings during fire.	Fire evacuation in a ten-storey telecom office building	FDS+Evac	Evacuation time, temperature field, smoke layer height, toxic gas index	70% of evacuation time is spent on stairs due to stoppages; exit numbers have minimal effect for small, familiar groups; adding an extra staircase can reduce evacuation time by 1/3.
[80]	Improve the accuracy of stair evacuation simulations by considering stair structure and evacuee fatigue.	Fire evacuation in high-rise buildings	Cellular Automata simulation model	Evacuation time, stair structure, evacuee fatigue	The new simulation, validated by fire drills, predicts evacuation time more accurately by incorporating fatigue; it provides valuable insights for building designers to develop better evacuation strategies.
[81]	Investigate evacuation strategies combining stairs and elevators in high-rise buildings.	Evacuation in a 28-storey building	Path finder	Evacuation time, elevator speed, elevator usage, occupant distribution	Optimal elevator usage is independent of the number of evacuees and floors; increasing elevator number reduces evacuation time more than increasing speed; prioritizing aged occupants for elevator use reduces congestion and speeds up evacuation. Lower-to-upper floor evacuation reduces stair congestion but slightly increases total evacuation time.
[82]	Analyze fire parameters and develop strategies for mitigating fire spread in high-rise buildings under construction.	High-rise construction fire simulation	FDS	Smoke, oxygen, temperature distribution, wind effect	Provides insights into fire behavior, including smoke and gas spread, and suggests strategies for effective fire prevention and control in high-rise buildings under construction.
[83]	Develop and validate an evacuation performance dataset for high-rise construction sites.	Evacuation of high-rise construction site workers	Modified building EXODUS	Response times, exit curves, performance metric, model validation	The study provides a reliable benchmark for evaluating evacuation simulations in high-rise construction sites, demonstrating that properly adapted simulation tools can offer accurate and practical insights for improving worker safety.

4 Results

In this section, the findings are presented through addressing the research questions.

4.1 RQ1: What are the key trends and characteristics of academic publications on fire evacuation?

In our study, the WOS database was utilized to review the scientific literature on fire safety evacuation. The time period was defined as between 2010 and 2025. The term "fire evacuation" was searched under "All Fields." A total of 3,364 academic publications on fire evacuation were evaluated, and the number of publications between 2010 and 2025 is presented in Figure 2. It was observed that there has been a general increase in publications on fire evacuation.

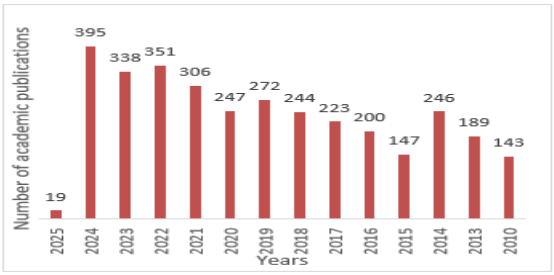

Figure 2. Number of academic publications.

Figure 3 presents the distribution of academic publications by WOS categories between 2010 and 2025. The top ten most frequently used fields in the WOS categories are tabulated. It was observed that the majority of studies on fire evacuation were conducted in the fields of Civil Engineering and Material Science. Although Occupational Health and Safety is not included in the top ten list, it ranks 17th with a share of 3.75%. In high-risk sectors such as construction, materials science, and industry, occupational health and safety is of critical importance. However, the 3.75% share of studies in this area indicates that it has not been sufficiently explored academically and that more research is needed. Increased academic research on occupational health could contribute to improving safety standards in workplaces and reducing risks through new technologies and methods. Therefore, expanding the share of occupational health in academic publications would provide significant benefits to both society and the workforce.

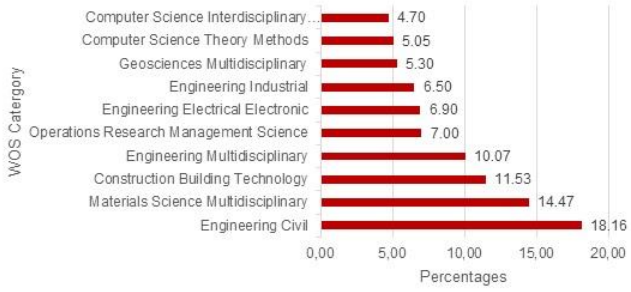

Figure 3. Distribution of academic publications by WOS categories.

Figure 3 shows the ranking of fire evacuation studies by country in WOS between 2010 and 2025, indicating that the highest number of studies were conducted in China, with a share of 38.4%. The United States follows with a share of 14.18%. This reflects the need for fire safety and evacuation practices due to high population density and the abundance of large buildings. The United Kingdom ranks third with 6.54%, followed by Australia at 5.05% and Japan at 4.99%. These developed countries have conducted a notable number of studies on fire safety.

Turkey, on the other hand, ranks 24th with a share of 0.86%. This low percentage indicates limited awareness of fire safety in the country and a lack of widespread use of fire evacuation systems. Therefore, various steps need to be taken to improve fire safety and evacuation systems in Turkey. These steps may include fire safety training and awareness programs, increased research, regular inspections, and investments in new technologies. Figure 4 below presents the percentages of evacuation studies conducted by country.

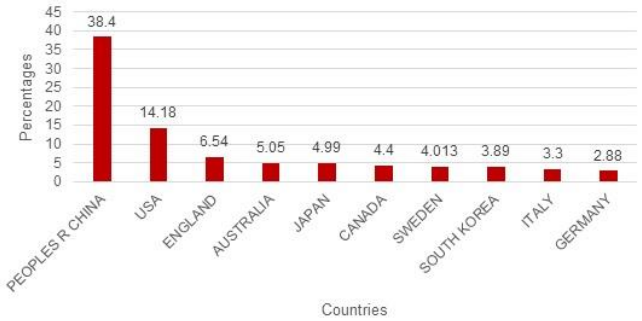

Figure 4. Percentages of evacuation studies by country.

4.2 RQ2: What are the main keywords used in fire evacuation research?

In this study, bibliometric analysis was conducted using VOSviewer to map the keywords of evacuation studies from 2010 to 2025. The analysis was carried out on 3,364 publications retrieved from the WOS database. Below are the detailed steps of the analysis process:

Step 1: Selecting the Type of Analysis

- The type of analysis was set to "Co-occurrence", which focuses on identifying how often specific keywords appear together in the same publications. This helps reveal the main research themes and their relationships.

Step 2: Setting up the Unit of Analysis

- The unit of analysis was specified as "Author Keywords", meaning the analysis was based on the keywords provided by the authors of the publications. This ensures that the key terms reflect the primary focus of each study.

Step 3: Defining the Minimum Number of Occurrences

- A minimum occurrence threshold of 3 was applied. This means that only the keywords appearing in at least three different publications were included in the analysis. This threshold was chosen to filter out less

relevant or rarely used keywords and focus on more significant terms.

Step 4: Generating the Keyword Map

- VOSviewer processed the data and created a bibliometric keyword map. In this map: Nodes represent the keywords. Node size indicates the frequency of each keyword. Larger nodes correspond to more frequently used keywords. Links between nodes show the co-occurrence of keywords, and the distance between nodes reflects how closely related the keywords are. Link strength quantifies the intensity of the relationship between keywords.
- "Fire safety" is linked to both "evacuation simulation" and "egress," indicating that fire safety is directly related to evacuation processes and designs. "Human behavior" is associated with "fire" and "evacuation," emphasizing that human behavior is a critical factor in evacuation planning during fires. Fire evacuation in high-rise buildings is directly linked to both "fire" and "evacuation," suggesting that high-rise buildings have unique evacuation requirements. "Tunnel fire" is connected to "fire safety," indicating that fire management in enclosed spaces is a specialized research area.

Step 5: Interpreting the Results

- In our study, it was observed that the focus of the research was on the keyword "Evacuation." In the figure, the distance between the nodes represents the co-occurrence frequency of keywords. The analysis revealed key research themes in fire evacuation studies, such as "Fire safety," "Evacuation simulation," "Human behavior," "High-rise building," and "Tunnel fire".
- These findings highlight that research trends in structural fires are particularly focused on high-rise buildings and tunnel fires. In line with our objective, detailed literature reviews on these two trending topics have been included in our study. The stages of our analysis conducted in VOSviewer are presented in Figure 5.

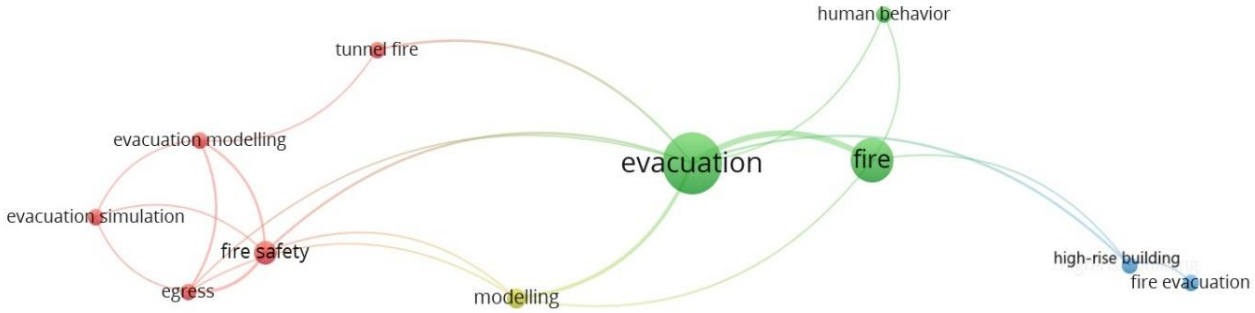

Figure 5. Bibliometric Mapping of Evacuation Study Keywords in VOSviewer for the Years 2010-2025.

4.3 RQ3: What is the scope of simulation use and the most prominent research trends in fire evacuation studies?

4.3.1 Tunnel/ metro stations bibliometric analysis

In this part of the study, a bibliometric analysis was conducted to identify fire evacuation studies focusing on tunnels, metro stations, and underground facilities. The Web of Science (WOS) database was used to retrieve relevant publications. Below are the detailed steps followed during the search:

Defining the Search Terms:

- To ensure that the search results included studies related to fire evacuation, simulation, modeling, and specific underground structures, the following key terms were used in “All Fields”: "Fire evacuation", "Simulation", "Modeling" and "Tunnel" OR "Metro" OR "Underground facilities".

Defining the search terms

- The search was limited to the period between 2010 and 2025, ensuring that the most recent and relevant studies were included in the analysis.
- The search yielded 61 publications directly related to fire evacuation in tunnels, metro stations, and underground facilities.

Bibliometric analysis

- This search yielded 61 publications.
- Type of analysis & Unit of analysis selection: The type of analysis was set to “Co-occurrence”, focusing on the co-occurrence of keywords. The unit of analysis was “Author Keywords” to capture the main topics of the studies.

- Threshold Setting: A minimum occurrence threshold of 2 was applied, ensuring that only keywords appearing in at least two different publications were included.
- Generating the map.
- Interpretation of the map: The bibliometric map is presented in Figure 6.
- Key Themes Identified:

"Numerical simulation", "fire evacuation", and "evacuation strategy" are closely linked, reflecting the emphasis on simulating evacuation scenarios and developing effective strategies.

"Emergency evacuation" and "cellular automata" form another cluster, indicating the use of advanced modeling techniques in simulating evacuation behavior.

- Clusters and Connections:

The yellow cluster, centered around "metro station", includes terms like "fire evacuation" and "evacuation efficiency", highlighting the importance of optimizing evacuation processes in metro environments.

The green cluster, with terms such as "numerical simulation" and "evacuation strategy", indicates a focus on using computational methods to model and improve evacuation strategies.

The blue cluster emphasizes "full-scale experiment" and "smoke", suggesting research that combines experimental validation with smoke propagation studies.

- Significant Observations:

The presence of terms like "cellular automata" and "web3d" highlights the use of advanced simulation and visualization tools in fire evacuation research for underground structures.

This analysis demonstrates that the primary focus of fire evacuation research in underground environments is on metro stations, with significant attention given to numerical simulations, emergency strategies, and smoke propagation. The identified clusters provide valuable insights into current research directions and potential areas for further investigation.

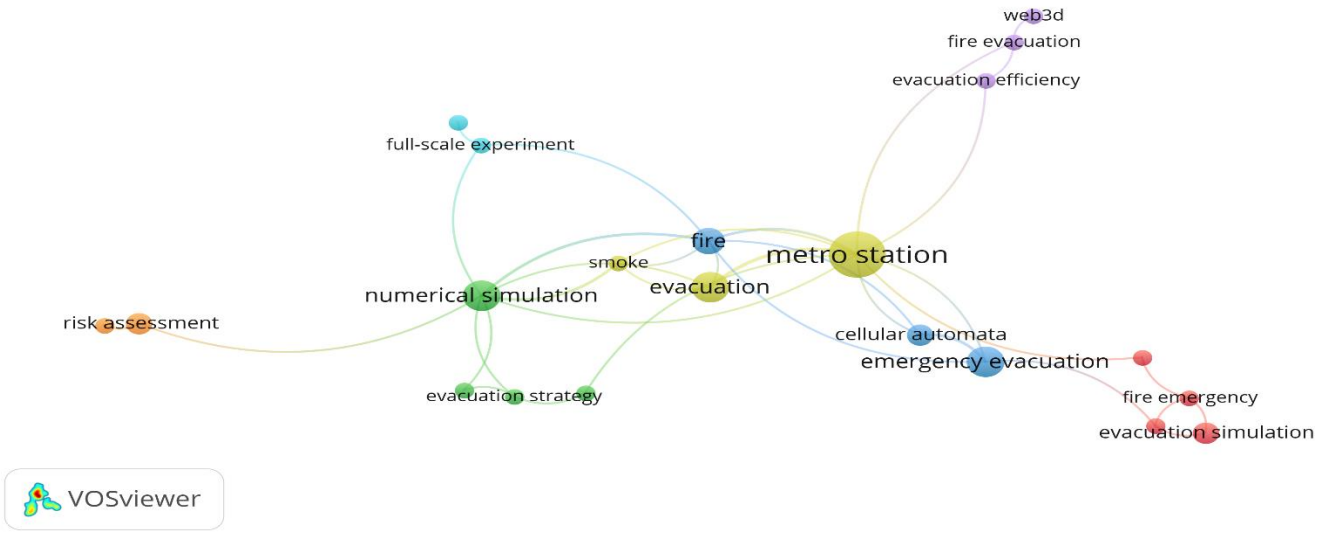

Figure 6. Bibliometric map of Metro Stations, Tunnels, and Underground Facilities.

4.3.2 High-rise building bibliometric analysis

To determine the scope of simulation use and identify prominent research trends in fire evacuation studies focused on high-rise buildings, a comprehensive search was conducted in the (WOS) database, followed by a bibliometric analysis.

Defining the search terms

- The search was designed to include the following key terms in “All Fields”: "Fire evacuation", "Simulation", "Modeling" and "High-rise building". These terms were chosen to target studies that incorporate both fire evacuation strategies and the use of simulation or modeling techniques in the context of high-rise buildings.

Setting the period

- Similar to the previous search, the time period was set between 2010 and 2025 to capture recent and relevant research on fire evacuation. Filtering the results
- The initial search returned 75 studies that met the criteria.

Bibliometric analysis

- This method allowed us to create a targeted dataset of 75 high-rise building evacuation studies, which was then used for further bibliometric analysis using VOSviewer. The selected studies provide a solid foundation for understanding key trends, methods, and findings in high-rise building evacuation research.

- Type of analysis & Unit of analysis selection: The type of analysis was set to “Co-occurrence”, focusing on the co-occurrence of keywords. The unit of analysis was “Author Keywords” to capture the main topics of the studies.
- Threshold setting: A minimum occurrence threshold of 2 was chosen, meaning that keywords appearing in at least two different publications were included in the analysis.
- Generating the map.
- Interpretation of the map: The bibliometric map is presented in Figure 7.
- Key Themes Identified:

The largest node, "high-rise building", is central to the map, indicating that it is the primary focus of these studies.

"Evacuation simulation" and "fire safety" are closely linked to "high-rise building," showing that simulation-based approaches and safety considerations are critical components of research in this area.

"Human behavior" and "phased evacuation" are important secondary topics, emphasizing the role of human factors and staged evacuation strategies in improving evacuation efficiency.

"Elevator", "stairwell", and "refuge floor" are key terms related to evacuation infrastructure, highlighting the unique challenges posed by high-rise buildings, such as the use of elevators and the need for designated safe areas.

- Clusters and Connections:

The map shows distinct clusters: The red cluster focuses on general safety, fire spread, and evacuation strategies involving stairs and elevators.

The blue cluster is centered around simulation and performance-based approaches, indicating that much of the research involves simulating evacuation scenarios to evaluate and improve evacuation strategies.

The green cluster includes terms like "phased evacuation" and "control volume model", suggesting research trends in advanced evacuation modeling techniques and phased strategies.

- Significant Observations:

This bibliometric analysis provides valuable insights into the key research themes, methodologies, and trends in high-rise building evacuation studies. The identified clusters and connections indicate that simulation, human behavior, and evacuation infrastructure are critical components of ongoing research in this field.

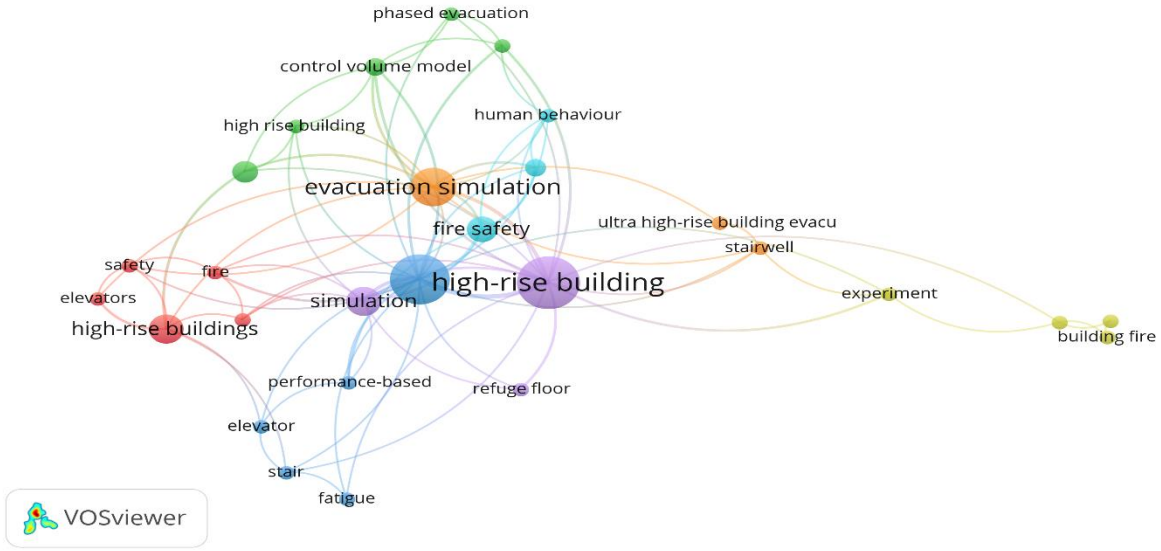

Figure 7. Bibliometric map of high-rise building evacuation studies.

4.4 RQ4: What are the key findings in fire evacuation research focused on high-rise buildings and tunnel fires?

4.4.1 Tunnel/ metro stations conclusion and findings

The analysis of 41 studies on fire evacuation simulations in tunnel/ metro stations has yielded the following key findings:
Significanca of Evacuation Modeling

- Emergency evacuation simulations for metro stations, tunnels, and large underground structures are critical for improving safety measures. These studies highlight the necessity of effective evacuation models to minimize risks during fire incidents.

Simulation Tools

- Most of the studies utilized advanced simulation software such as AnyLogic, FDS, Pathfinder, and Simulex. These tools enabled realistic modeling of evacuation scenarios and helped assess the impact of various factors on evacuation efficiency.

Key Factors Influencing Evacuation

- Bottlenecks: Narrow areas such as stairways, passageways, and gates were identified as the main factors prolonging evacuation time.
- Smoke and Fire Spread: The spread of fire and smoke directly impacted passenger movement speed and evacuation route choices.

- Passenger Behavior: Human factors such as crowd density, group movement, and reaction time played a crucial role in determining the overall evacuation time.

Proposed Solutions

- Physical improvements, including widening stairways and optimizing exit placements, were frequently recommended.
- Several studies proposed risk evaluation methods to identify high-risk areas during evacuation.
- Redesigning entry and exit points and optimizing ticket gate systems were suggested to balance passenger flow and reduce congestion during emergencies.

Scenario-Based Analysis

- The studies typically modeled different scenarios (e.g., varying fire outbreak locations, passenger density levels, and flow distributions) to develop tailored solutions. This approach ensured comprehensive risk assessment and provided actionable insights for station design improvements.

General Conclusion

- Overall, these studies demonstrate that comprehensive simulation-based analyses can significantly enhance evacuation safety in underground transportation systems. By incorporating real-world data and simulating various emergency conditions, these studies offer practical solutions for optimizing metro station and tunnel evacuation strategies.

4.4.2 High-rise buildings conclusion and findings

The analysis of 34 studies on fire evacuation simulations in high-rise buildings and complex structures has yielded the following key findings:

Key Factors Affecting Evacuation Time

- Stairway and Exit Design: The width, location, and number of stairways and exits directly influence evacuation time. Narrow stairways and limited emergency exits create significant bottlenecks during evacuation.
- Fire Origin Location: When a fire starts on the lower floors, the evacuation process becomes more complicated for upper floors, resulting in increased evacuation time.
- Psychological and Physical Conditions: Vulnerable groups such as the elderly and children significantly slow down the evacuation process due to their limited mobility.

Role of Evacuation Models and Simulation Tools

- Tools like Pathfinder and AnyLogic: These tools facilitated the analysis of various scenarios and parameters, providing critical insights into optimizing evacuation strategies and reducing evacuation time.
- BIM and ABM Integration: The integration of Building Information Modeling (BIM) and Agent-Based Modeling (ABM) has allowed more realistic three-dimensional simulations, enhancing decision-making during emergency planning.

Proposed Strategies and Improvements

- Use of Refuge Areas: The inclusion of refuge areas in high-rise buildings improves safety and reduces evacuation time by providing temporary shelter during emergencies.
- Psychological Factors and Group Dynamics: Family groups negatively impact evacuation efficiency by causing congestion. Solo evacuations or smaller group sizes result in faster evacuation times.
- Elevator Use: Properly managed elevator usage in emergencies can significantly improve evacuation outcomes, especially for vulnerable populations.

Complex Scenarios and Multi-Tool Analysis

- Several studies compared different simulation tools to enhance the accuracy of evacuation models and strategies. The combination of microscopic models (e.g., Pathfinder) and macroscopic models (e.g., Evacuationz) provided a broader analysis of scenarios involving varying stairway widths, building sizes, and evacuee characteristics.

General Assessment

- These studies demonstrate that simulation-based approaches are indispensable for minimizing risks and improving safety during evacuations in high-rise buildings. Modeling realistic scenarios has facilitated critical improvements in both structural design and emergency procedures. The incorporation of human behavioral characteristics into evacuation processes has enabled the development of more effective evacuation plans.
- Overall, the findings offer valuable guidance for building designers, fire safety engineers, and emergency planners in enhancing fire safety and evacuation efficiency.

5 Conclusion and future work

This study presents systematic and detailed literature mapping in the area of fire evacuation, focusing on high-rise buildings and underground facilities, to identify key research trends and methodologies between the years 2010 and 2025.

Through targeted searches in the Web of Science (WOS) database and subsequent analysis, the study achieved its objective of understanding the scope of fire evacuation studies in these two critical environments. The results provide a clear overview of existing research gaps and highlight the importance of simulation-based approaches in improving evacuation safety.

The analysis of these studies was conducted based on the defined research questions, and the resulting outcomes offer several significant insights, as outlined below:

- Mapping of Research Trends: Existing studies in the literature have been reviewed, and the areas in which these studies are predominantly concentrated have been identified. This analysis helps to detect research gaps and provides a framework that can guide future studies.
- Identification of Application Areas: By highlighting the sectors or structural environments where simulation and modeling techniques are more frequently utilized, strategies can be developed to enhance the effective use of these techniques.
- Observations on the Applicability of Simulation Methods: Although the study does not directly address specific simulation software or modeling approaches in detail, general observations were made based on the purposes of the reviewed literature regarding the potential applicability of certain

simulation methods in similar studies. In this context, it has been highlighted that a comprehensive classification of simulation techniques applicable to fire evacuation processes could be developed, and methodological diversity in this field could be enhanced.

Future research could further explore comparative evaluations of different simulation tools and their effectiveness in various architectural contexts. Additionally, studies focusing on real-time evacuation modeling, the integration of human behavior dynamics, and the application of AI-based approaches could significantly enhance fire evacuation planning. Developing a structured classification of simulation methodologies and establishing standardized evaluation metrics would also support both academic studies and practical implementations. These directions can guide future work in creating more robust, adaptive, and context-specific evacuation models.

6 Author contribution statements

Within the scope of this study, Author 1 and Author 2 jointly took part in the formation of the idea. Author 1 contributed to this study on literature review, methodology creation, obtaining results, and writing the original draft. Author 2 contributed to content review and editing of the article and also supervised the whole study.

7 Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared. There is no conflict of interest with any person/institution in the article prepared.

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