

CITY-SCALE RISK MONITORING OF HIGH-RISE RESIDENTIAL BUILDINGS
FOR FIRE DISASTER PREPAREDNESS

by

Mustapha Muazu Jodi

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ABSTRACT

CITY-SCALE RISK MONITORING OF HIGH-RISE RESIDENTIAL BUILDINGS FOR FIRE DISASTER PREPAREDNESS

Resilience to potential disasters is of paramount importance in rapidly expanding urban environments. During such events, the primary objective is timely evacuation of occupants to ensure safety. Response authorities often lack a comprehensive understanding of occupant behavior in high-rise buildings, which is crucial for operational and mitigation control. Moreover, the lack of integrated software for planning and managing disaster events has exacerbated this issue. This study addresses that gap by developing an integrated framework that strengthens the fire disaster preparedness of high-rise residential buildings. An agent-based evacuation simulation and regression analysis are employed to model the time history of occupant egress during emergency scenarios, capturing floor-by-floor clearance dynamics of a high-rise residential building in the city. In parallel, a GIS-based network analysis estimates response-arrival intervals for fire brigade vehicles travelling through the urban street network to each building site. Building on these insights, a spatial processing application that links simulated evacuation timelines with the geographic distribution of emergency response assets is implemented. Evacuation model outputs reveal that the rate at which successive floors are evacuated increases linearly with total building height after a threshold floor occupancy is reached, underscoring the operational importance of early intervention in taller structures. The resulting framework quantifies the spatial relationship between population clusters and responder locations, enabling data-driven allocation of fire preparedness and response resources.

ÖZET

YANGIN FELAKETİNE HAZIRLIK İÇİN YÜKSEK KATLI KONUTLARIN ŞEHİR ÖLÇEĞİNDE RİSK İZLEMESİ

Potansiyel afetlere karşı dayanıklılık, hızla genişleyen kentsel ortamlarda büyük önem taşımaktadır. Bu tür olaylar sırasında birincil amaç, güvenliğini sağlamak için yolcuların zamanında tahliyesidir. Müdahale yetkilileri genellikle, operasyonel ve azaltma kontrolü için çok önemli olan yüksek binalardaki bina sakinlerinin davranışlarına ilişkin kapsamlı bir anlayıştan yoksundur. Ayrıca, afet olaylarını planlamak ve yönetmek için entegre yazılım eksikliği bu sorunu daha da kötüleştirdi. Bu çalışma, yüksek katlı konut binalarının yangın afetine hazırlığını güçlendiren entegre bir çerçeve geliştirerek bu boşluğu ele almaktadır. Acil durum senaryoları sırasında bina sakinlerinin çıkışının zaman geçmişini modellemek için ajan tabanlı bir tahliye simülasyonu ve regresyon analizi kullanılır ve şehirdeki yüksek katlı bir konut binasının kat kat boşluk dinamiklerini yakalar. Buna paralel olarak, CBS tabanlı bir ağ analizi, kentsel sokak ağı üzerinden her bir şantiyeye seyahat eden itfaiye araçları için tepki-varış aralıklarını tahmin eder. Bu içgörüler üzerine inşa edilerek, simüle edilmiş tahliye zaman çizelgelerini acil durum müdahale varlıklarının coğrafi dağılımıyla ilişkilendiren bir uzamsal işleme uygulaması uygulanır. Tahliye modeli çıktıları, ardışık katların tahliye edilme hızının, bir eşik kat doluluğuna ulaşıldıktan sonra toplam bina yüksekliği ile doğrusal olarak arttığını ortaya koymakta ve daha yüksek yapılarda erken müdahalenin operasyonel önemini vurgulamaktadır. Ortaya çıkan çerçeve, nüfus kümeleri ve müdahale konumları arasındaki mekansal ilişkiyi ölçerek, yangına hazırlık ve müdahale kaynaklarının veriye dayalı tahsisini sağlar.

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LIST OF SYMBOLS

A	Floor area
A_i	Floor area of building i
$c_{ij}(\tau)$	Minimum-impedance path cost between origin i and destination j
c_p	Heat capacity of air under constant pressure
C_1, C_2, C_3, C_4	Criteria values in site suitability analysis
D	Occupant population density
D^*	Characteristic fire diameter
$E(t)$	Cumulative number of occupants evacuated by time t
$E_f(t)$	Cumulative number of occupants evacuated from floor f by time t
F	Number of floors in building
F_p	Congestion factor for peak traffic
F_s	Occupant flow rate
$F_{s,max}$	Maximum achievable occupant flow rate
G	Stair tread depth
g	Gravitational acceleration
H	Heaviside step function
H_i	Building height (number of floors)
$I_{Voronoi}$	Voronoi importance index
k	Fire ignition rate parameter
K	Extinction coefficient
L_i	Segment length
n	Number of buildings in Voronoi polygon
N	Total number of buildings in city
N_f	Number of occupants on floor f
P_i	Probability of fire occurrence
Q	Heat release rate

$q[k]$	Evacuation flow rate at time interval k
R	Stair rider height
$R_{Voronoi}$	Voronoi risk index
S	Occupant speed
S	Suitability score in multi-criteria analysis
t	Time variable
t_i	Exit time of occupant i
T_f	Floor clearance time for floor f
T_∞	Ambient temperature
TT_{off}	Off-peak travel time
TT_{peak}	Peak-hour travel time
V	Fire vulnerability index
V_i	Posted speed limit
w_1, w_2, w_3, w_4	Weights in multi-criteria site suitability analysis
$\bar{x}, \bar{y}$	Coordinates of optimal fire station location
α	Fire growth rate
α_i	Percentage increase of TET due to fire
β	Number of floors (building height parameter)
γ	Number of occupants per floor
Δt	Time interval
μ	Statistical mean value
ρ_∞	Ambient air density
σ	Standard deviation
τ	Time parameter for network analysis

LIST OF ACRONYMS/ABBREVIATIONS

AHP	Analytic Hierarchy Process
ASET	Allowable Safe Evacuation Time
ASTM	American Society for Testing and Materials
BYKHY	Binaların Yangından Korunması Hakkında Yönetmelik (Regulation on Fire Protection of Buildings)
CFD	Computational Fluid Dynamics
CFL	Courant-Friedrichs-Lewy
EHS	English Housing Survey
EHVAC	Evacuation History Visualizer and Curator
EPSG	European Petroleum Survey Group
ESRI	Environmental Systems Research Institute, Inc.
FDS	Fire Dynamics Simulator
FRA	Fire Risk Assessment
FRR	Fire Resistance Rating
FRT	Fire Brigade Response Time
FSE	Fire Safety Engineering
GIS	Geographic Information System
GPS	Global Positioning System
GUI	Graphical User Interface
İBB	İstanbul Büyükşehir Belediyesi (Istanbul Metropolitan Municipality)
IBC	International Building Code
İBS	İtfaiye Bilgi Sistemi (Fire Department Information System)
IMO	International Maritime Organization
ISO	International Organization for Standardization
LES	Large Eddy Simulation
MVC	Model-View-Controller
NBFU	National Bureau of Fire Underwriters

NIST	National Institute of Standards and Technology
NFPA	National Fire Protection Association
NRI	Network Robustness Index
OD-matrix	Origin Destination Matrix
OSM	OpenStreet Map
PDF	Probability Density Function
PRA	Probabilistic Risk Assessment
RHR	Rate of Heat Release (Heat Release Rate)
RSET	Required Safe Evacuation Time
SFPE	Society of Fire Protection Engineering
TET	Total Evacuation Time
TÜİK	Türkiye İstatistik Kurumu (Turkish Statistical Institute)
UAVT	Ulusal Adres Veritabanı (National Address Database)
UTM	Universal Transverse Mercator
V&V	Verification and Validation
WGS	World Geodetic System

1. INTRODUCTION

1.1. Motivation

In many cities today, high-rise residential development continues to emerge as a vital component of the modern cityscape. Fire emergencies in such densely populated buildings can escalate rapidly if preparedness measures are not robust and well-coordinated. Tools that facilitate real-time or near real-time risk assessments help stakeholders remain compliant and responsive to evolving safety standards. This increasing number of tall buildings in cities around the world introduces a corollary challenge: while these structures provide vital housing solutions, they also introduce unique vulnerabilities. Traditional fire safety measures—centered on individual buildings—may prove insufficient when the scope extends to a district or entire city. High-density living not only concentrates risk but also complicates evacuation procedures, fire suppression efforts, and inter-agency coordination.

Two emblematic incidents in Türkiye’s recent history demonstrate the necessity of a city-scale fire risk monitoring system. The Polat Tower blaze on 17 July 2012 in a 42-storey mixed-use skyscraper in Şişli, Istanbul, ignited by a faulty air-conditioning unit and propagating rapidly along the external façade, was ultimately contained without casualties but exposed critical challenges in routing fire-fighting units through dense urban road networks. In stark contrast, the Grand Kartal Hotel fire at the Kartalkaya ski resort on 21 January 2025 claimed 78 lives after the absence of sprinklers, alarms, and well-mapped service areas delayed first-responder arrival. Together, these case studies demonstrate that building-level safety measures and localized evacuation plans, while essential, must be integrated within a broader *data-driven* framework to proactively anticipate, manage, and mitigate fire risk across Istanbul’s complex urban fabric.

Against this backdrop, *resilience* serves as a guiding paradigm: it shifts the focus from merely reacting to fire incidents toward building robust systems and policies that

enable urban areas to anticipate, manage, and swiftly recover from disasters. Fire risk monitoring, when executed at scale, becomes a critical component in a wider resilience framework, uniting analytical tools, stakeholder engagement, and emergency planning under a common vision of safer, more adaptable cities. The motivation behind this research stems from the urgent necessity to devise comprehensive, city-scale risk monitoring systems that can not only anticipate and detect fire-related emergencies but also facilitate efficient preparedness and response strategies.

In recent decades, the availability of geospatial data, advanced Geographic Information System (GIS) platforms, and sophisticated spatial analysis techniques have significantly improved the ability to reliably monitor urban risk at a large scale. GIS-based spatial analysis allows for the identification of vulnerable locations, the optimization of emergency response resource allocation, and the continuous monitoring of urban hazards. This research leverages these capabilities to inform city-scale fire risk monitoring, with the overarching goal of enhancing fire disaster preparedness and response for the Municipality of Istanbul, Türkiye.

City-scale monitoring of fire risk in high-rise buildings is not just a safety measure—it is a multidimensional challenge that intersects urban planning, technology, and public policy. This includes integrating state-of-the-art sensing technologies, real-time data analytics, and advanced communication networks into a unified risk monitoring framework offers a transformative approach to disaster management. Such integration empowers city authorities to dynamically monitor structural integrity, environmental conditions, and potential ignition sources across entire urban regions. It also enhances predictive capabilities, enabling preventive actions that can save lives and reduce property damage.

A data-driven approach is therefore indispensable to building a robust fire disaster preparedness system that identifies, assesses, and monitors fire hazards at a city-wide scale. In other words, understanding the distribution of vulnerabilities and optimizing emergency response is critical for informing *evidence-based* decision-making in urban

fire risk management to align limited resources with the locations and populations most in need.

In this study, occupant evacuation modeling is used to trace floor-by-floor occupant evacuation timeline to highlight internal bottlenecks; spatial and network analyses are utilized alongside a risk assessment framework to systematically monitor city-scale fire risk. Spatial analysis helps to pinpoint areas with higher fire vulnerability, while network analysis evaluates accessibility and optimal routes for emergency response. By developing and implementing an effective city-scale risk monitoring system, municipal authorities can optimize resource allocation, improve emergency response times, and foster a safer living environment.

1.2. Urban Fire Risk

Disaster prevention refers to the proactive measures taken to minimize risk factors and reduce the likelihood of hazardous events before they occur by addressing their underlying causes. Unlike preparedness—which focuses on ensuring readiness to cope with hazard—prevention places emphasis on early interventions that minimize or remove risk altogether. In the context of urban fire safety, prevention involves an array of measures such as stringent construction codes for high-rise buildings, installation of advanced fire detection systems, and continuous evaluation of hazardous materials. These strategies collectively aim to prevent fire events from unfolding on a large scale, thereby safeguarding human lives and property.

In practice, however, preventing fire disasters in sprawling urban centers requires both technological infrastructure and organizational readiness. On the technological front, sensor networks and real-time data analytics facilitate the early detection of anomalous conditions—such as escalating temperatures or smoke—that could trigger fires. These warning signals can then be relayed to emergency services, enabling swift intervention. Equally important is the organizational structure that coordinates these technologies, ensuring data flows seamlessly among municipal agencies, building

managers, and first responders.

Disaster management encompasses a coordinated and systematic approach to handling emergencies from onset to resolution. It integrates planning, resource allocation, and rapid response to minimize the adverse impacts of disasters while fostering an environment that facilitates speedy recovery. In the context of urban fire emergencies, disaster management is particularly critical due to the complex interplay between high-density living, intricate building structures, and the heightened risk of cascading hazards.

At its core, disaster management involves four interconnected phases:

- (i) Mitigation: actions designed to reduce risk and prevent disasters from occurring.
- (ii) Preparedness: Strategies and planning measures that enable rapid and effective response when disasters strike.
- (iii) Response: The immediate actions taken during an emergency to save lives, protect property, and contain the event.
- (iv) Recovery: Efforts aimed at restoring normalcy and improving resilience in the aftermath of a disaster.

This study advances the disaster-preparedness literature by isolating the key determinants of evacuation and emergency response times and translating those insights into evidence-based recommendations that strengthen community resilience. Although this thesis centers on fire preparedness—ensuring that residents and authorities can respond swiftly and effectively once an emergency occurs—it also acknowledges the foundational importance of fire prevention. Effective preparedness is most robust when anchored in a broader risk-mitigation framework. In this regard, GIS-based spatial analysis and modeling are indispensable: by mapping building attributes (e.g., height, construction materials, occupancy), historical fire-incident patterns, population densities, and infrastructure layers such as road networks and fire-station locations, planners can pinpoint high-risk zones and underserved areas. These geospatial insights

enable municipal decision-makers to optimize resource placement, amend regulations, and implement targeted infrastructural upgrades, thereby fostering safer and more resilient urban environments.

1.3. Research Question

The ability to rapidly discern critical signals from background noise is crucial in mitigating risk and ensuring public safety. Equally important is the need for adaptability in the emergency response framework. Urban disasters are inherently unpredictable, and static response plans can quickly become obsolete in the face of evolving circumstances. By embracing an adaptable operational strategy, authorities and emergency teams can dynamically adjust their actions as new information becomes available.

The present work investigates an integrated approach of combining occupant evacuation data with spatial analysis to strengthen a city's fire preparedness and response plan. This requires a methodological bridge between detailed building-scale simulations and city-wide network analysis. The study examines both methods of monitoring risk as well as of those of optimally directing resources to minimize the potential cost of lives due to fire disaster in high-rise residential buildings.

The central research question asks: *How can building-level evacuation analytics be effectively integrated with city-scale network model to reduce the combined occupant evacuation and fire brigade response time for high-rise residential fires?* The research objectives are achieved through analyzing historical fire occurrence data including incident locations, timings, and extinguishing durations and effectively visualizing them to enhance understanding of urban fire risk. This inquiry is directed at unveiling hidden patterns and trends within complex datasets related to past fire incidents. Visualization of the available data is also intended to provide emergency responders and city planners with critical insights for resource allocation, inform policy discussions on fire risk mitigation. Ultimately, this approach fosters a data-driven culture where both technical and non-technical stakeholders can collaborate effectively towards enhancing

urban safety.

Moreover, given the current locations of existing fire stations, optimal locations for new fire stations in the city can ensure improved coverage and reduced response times for high-rise residential structures. The research employs multi-criteria decision analysis and network analytics. Spatial data on existing fire station locations, high-rise building densities, and city road network characteristics are utilized to evaluate accessibility and response dynamics across Istanbul's urban landscape. This part of the study is essential for formulating actionable recommendations that support efficient emergency operations and resource planning, ultimately enhancing the overall resilience of Istanbul's urban fabric.

Research is rapidly moving toward digital twin platforms where live sensor feeds update real time crowd models, enabling building managers to issue dynamic routing advice and emergency services to synchronize arrival with on going egress. For Istanbul, integrating citywide traffic feeds with agent based egress outputs offers a pathway to holistic city scale fire evacuation planning. Maps that identify regions with high probability of exceeding time thresholds can guide both permanent station placement and temporally adaptive deployments.

1.4. Scope and Limitation

The scope of this thesis is centered on Istanbul's high-rise (15 stories or more) residential buildings and the municipal-scale fire preparedness strategies that can be informed through spatial analysis. The study utilizes existing geospatial datasets, which include data of Istanbul's high-rise residential buildings, current fire station locations, and historical fire incident records. The incident data utilized covers a full calendar year.

Moreover, active fire protection systems such as automatic sprinkler networks, smoke detectors, and alarm infrastructures are not explicitly modeled in this analysis.

Incorporating their performance would require building-level engineering models and maintenance records that extend beyond the city-scale-focused framework employed here. Consequently, this research adopts a baseline “passive safety” assumption and concentrates on spatial and network factors that govern evacuation and emergency-response dynamics.

As mentioned, the analytical framework this study is organized around two reinforcing components that together contribute to a comprehensive city-scale vulnerability and fire risk assessment. The first component involves a parametric simulation of evacuation scenarios within existing high-rise residential buildings. This simulation examines how varying building characteristics and occupancy conditions affect evacuation efficiency and safety. Although the findings illuminate broad patterns and critical thresholds, the precision of risk estimates and their generalizability remain constrained by the simplifications inherent in demographic averaging—an issue that future research can address through richer behavioral datasets and real-time sensing.

The second component of the risk monitoring framework involves city-wide spatial analysis. The assumptions made in this regard determine the accuracy of the results obtained. Moreover, the geospatial dataset is two-dimensional. Consequently, the spatial model captures first-order patterns in service accessibility, and its applicability to real-time operations remains contingent on the traffic and evacuation behavior data feeds.

1.5. Thesis Outline

This thesis is organized into seven chapters. The first chapter provides an overview of the study’s motivation, importance of fire disaster prevention and management, as well as research questions, scope, and limitations. It also outlines the structure of the thesis. Chapter 2 examines existing research on fire risk assessment, occupant evacuation analysis and the role of GIS in emergency management and location-allocation for emergency services.

Chapter 3 details the theoretical foundation of the risk monitoring framework. The chapter discusses the occupant evacuation simulation methodology, key parameters influencing occupant behavior, and the implications of the simulation results on emergency management practices. The chapter also describes the methods employed to conduct spatial analysis, determine optimal fire station locations. This is discussed in the context of city-scale resilience, and the potential application of these methods in other metropolitan settings.

Chapter 4 provides details of the datasets utilized, including buildings and fire stations, and historical fire incident records as well as the setting in which the data were acquired and the context in which they are utilized.

In Chapter 5, the findings from the parametric simulation of evacuation scenarios within Istanbul's high-rise residential buildings is presented. It examines how variations in building characteristics impact evacuation times. Chapter 6 shifts to a broader analysis of Istanbul province and city using spatial analysis tools. Here, the integration of the simulation results with the urban network analysis is explored to assess and monitor fire risk, evaluate emergency response efficiency, and determine optimal fire station placements.

Finally, Chapter 7 provides further interpretation of the results from the previous two chapters, elucidating the findings advance our understanding of Istanbul's fire preparedness. It then examines the broader implications of these insights for urban fire disaster preparedness—particularly the roles of urban form, road connectivity, and high-rise density in shaping city-scale resilience. Building on that, the chapter presents targeted recommendations for enhancing Istanbul's fire disaster preparedness strategy.

2. LITERATURE REVIEW

Urban fires have historically imposed significant socio-economic costs yet have received less scholarly attention compared to other urban hazards (Goswami et al., 2024; Jennings, 2013). Rapid urbanization and high population densities in cities have amplified the potential for fire disasters. Fire risk in buildings has been a critical concern since the earliest urban settlements, evolving alongside architectural and technological advancements. The Great Fire of London (1666) and the Great Boston Fire (1872) catalyzed the development of systematic approaches to fire safety, leading to regulatory codes and insurance frameworks that continue to evolve today (Babrauskas, 2017). These historical events highlighted the catastrophic consequences of uncontrolled urban fires and the need for coordinated prevention and response strategies.

Innovations in fire-resistant materials, compartmentation, and automatic suppression systems have reduced fire incidence severity. Material properties underpinning fire ignition and growth have been re-examined, with (Babrauskas, 2017) proposing engineering-based variables to supersede the traditional "non-combustibility" concept. Under most building codes this concept is treated as a binary pass/fail label—materials that do not ignite or sustain flaming under small-scale tests are classified as *non-combustible*, whereas everything else is deemed *combustible* (ASTM International, 2023; International Organization for Standardization, 2020). However, enforcement challenges emerge in retrofit contexts, where inspections of façade cladding, common in high-rise residential buildings, are irregular (McKenna et al., 2019).

In Türkiye, (Türkiye Yangından Koruma ve Eğitim Vakfı, 2012), the regulation on fire protection of buildings (BYKHY), mandates minimum fire-resistance ratings (FRR) for structural adequacy, integrity and insulation as well as suppression system requirements in tall structures alongside sprinkler installations above specified heights. Ongoing efforts to harmonize Turkish standards with international standards such as those of the United States-based National Fire Protection Association–NFPA 101

(National Fire Protection Association, 2024) seek to elevate occupant safety benchmarks, especially for mixed-use high-rises. For instance, Table 2.1 shows a comparison between several international building codes regarding the minimum occupancy level to be considered for building fire safety.

Table 2.1. Occupant Load Factor for residential buildings.

Fire Safety Code	Occupant Load Factor
BYKHY	20 m ² /person (occupied area)
IBC and NFPA 101	18.6 m ² /person for (gross leasable area)
Approved Document B	8.0 m ² /person (bedrooms)
New Zealand C/VM2	Number of bed spaces and staff when appropriate
Hong Kong COP	4.5 m ² /person (≥ 5 flats served by each staircase)
	9 m ² /person (other flats)

Researchers have drawn attention to the interplay between rapid urbanization, infrastructural constraints, and evolving building technologies, all of which contribute to the heightened risk profile observed in modern cities. The following sections review the literature that have investigated building fires, occupant movement in buildings, fire brigade emergency response during fire events and risk assessment frameworks.

2.1. Building Fires

(He et al., 2003) highlighted that fire safety engineering (FSE) is fundamentally risk reduction engineering, requiring systematic methods to quantify and mitigate various hazards. Traditional deterministic approaches typically focus on worst-case scenarios without considering the likelihood of various outcomes, resulting in overly conservative estimates (Ramachandran, 1990). In contrast, Probabilistic Risk Assessment (PRA) provides a more nuanced understanding of potential fire scenarios and their consequences by incorporating uncertainty analysis.

Recent studies have developed multi-factor frameworks for examining building fires in urban settings, incorporating variables such as fire control management, facility maintenance, firefighting capacity, and other human factors (Bai and Liu, 2023). (Feliciani and Nishinari, 2018) characterized risk sources as intrinsic (e.g., physical ability, panic susceptibility) and extrinsic (e.g., signage clarity, alarm audibility), suggesting layered mitigation strategies such as improved wayfinding, powered egress lighting, and occupant training to reduce pre-evacuation delays and maintain throughput during emergencies.

(Lin, 2004) conducted pioneering work on life risk analysis in residential building fires, demonstrating that certain building and occupant characteristics could effectively discriminate between fatal/injurious fires and non-fatal/non-injurious ones. Through logistic regression analysis, (Lin, 2005) identified the most significant factors affecting life risk as firefighting conditions, difficulty of fire escape, and the presence of disabled people in buildings, establishing a quantitative basis for vulnerability assessment.

Another significant challenge in fire risk assessment is estimating the probability of fire occurrence. Fire initiation in urban buildings typically follows classification into accidental (cooking, electrical faults), natural (lightning), or malicious (arson) origins. The Rate of Heat Release (RHR) curve underpins fire growth modeling: stages of growth, flashover, and decay are characterized by t^2 ("t-squared") or other empirical growth laws (Drysdale, 2011). (Lin, 2005) proposed a Poisson process model for fire initiation, using mean annual fire rates based on building floor area and historical incident data. This approach enables the estimation of fire occurrence probabilities for different building types and occupancies, revealing that while industrial occupancies have the highest ignition rate per unit area, residential occupancies account for the highest total fire ignitions due to their prevalence in the built environment.

2.2. Crowd Dynamics

Crowd-safety research views evacuation failures as systemic—rarely caused by a single flaw but by multiple vulnerabilities lining up. (Haghani et al., 2023) frames this via the Swiss-cheese model, in which each "slice" (building codes, alarms, egress capacity, training) contains latent holes; when holes align, a disaster path opens. This framework emphasizes the importance of overlapping safeguards that compensate for one another rather than relying on any single remedy, aligning with modern risk management principles that recognize the complex, multi-factorial nature of disaster events. This overview establishes the theoretical and empirical basis for the occupant-evacuation analyses presented in Chapter 5.

2.2.1. Fundamental Movement Models

The foundational concepts of building egress design date back to the early 17th century, when François Blondel conducted pioneering studies on stair geometry, establishing the relationship $2R + G = 24$ inches (where R represents riser height and G represents tread depth) for optimal comfort in stair design (Bukowski and Tubbs, 2016). This formula, while initially focused on comfort rather than safety, laid the groundwork for quantitative approaches to evacuation path design.

Modern fire safety engineering emerged in the late 19th and early 20th centuries with significant advancements following the 1872 Great Boston Fire, which led to the formation of the National Bureau of Fire Underwriters (NBFU) after numerous insurance companies faced bankruptcy due to the catastrophic losses (Bukowski and Tubbs, 2016). The NBFU subsequently published the first model building code in 1905, establishing minimum doorway width requirements of 510 mm, which was later refined through successive NFPA conferences. (Bukowski and Tubbs, 2016). Subsequent developments led to the establishment code language and collecting data on exit sizes, population distribution, movement dynamics, and discharge rates (Chalmet et al., 1982; Gwynne and Rosenbaum, 2016). Confirmed correlation between exit width and flow

rate, suggesting five potential methodologies for calculating evacuation time used by the Society of Fire Protection Engineering (SFPE): capacity method, flow method, combined method, probability method, and floor area method.

The quantification of human movement during evacuation has been a central focus in fire safety research. (Predtechenskii and Milinskii, 1978) established the first comprehensive quantitative relationships between occupant density, walking speed, and flow rate, which were later refined by (Virkler and Elayadath, 1994) into a set of linear and non-linear models. Their work compared seven different mathematical relationships between pedestrian speed, density, and flow, finding that Edie's discontinuous exponential form provided the most accurate predictions of pedestrian movement across different density regimes.

The hydraulic model, widely adopted in fire safety engineering, treats pedestrian flow analogously to fluid dynamics, establishing relationships between component width, flow density, and evacuation speed (Gwynne and Rosenbaum, 2016). This model forms the basis for the SFPE calculation methods, which quantify the maximum flow (persons/min/m) through exit components based on their effective width.

However, (Gwynne et al., 2009)'s the assumption of a simple linear relationship between doorway width and flow rate, demonstrating that door mechanisms and actual usage patterns significantly influence achieved flow rates. Their analysis of unpublished camera footage data revealed that the average door width available during actual evacuations was approximately 75% of the nominal width, significantly affecting theoretical capacity calculations.

(Daamen and Hoogendoorn, 2010) further investigated doorway capacities during evacuation conditions, examining how factors such as doorway width, population composition, door configuration, and stress level affect flow rates. Their laboratory experiments demonstrated that wider openings often resulted in lower-than-expected capacities, while stress levels and population demographics (particularly the presence

of children or disabled participants) significantly influenced achieved flow rates. They also found that doors opened at 90 degrees in the escape direction reduced capacity by approximately 20% for standard-width openings.

(Hopkin et al., 2019) analyzed residential occupant density distributions using English Housing Survey (EHS) data, demonstrating limitations in traditional occupant load assumptions used in building codes. Their work revealed significant variations in actual occupancy patterns compared to standard density assumptions (e.g., $20\text{m}^2/\text{person}$), suggesting that more nuanced approaches based on number of bedrooms or statistical distributions might better represent actual conditions, particularly for estimating potential fire exposure.

(Hopkin et al., 2021) conducted research on door opening time distributions for evacuees, quantifying how physical door operations affect overall flow rates and evacuation efficiency. This work complements (Gwynne et al., 2009) findings on the nonlinear relationship between doorway width and flow rate, providing a more complete understanding of bottleneck dynamics in building evacuations.

Behavioral aspects of evacuation have received increased attention as researchers recognize that human decision-making significantly impacts evacuation outcomes. Pre-evacuation phases—information processing and decision-making—often consume 30-120 seconds, influenced by alarm type, occupant awareness, and building signage (Gwynne and Rosenbaum, 2016; Oven and Cakici, 2009). This delay can significantly impact overall evacuation times, particularly in high-rise buildings where vertical egress demands are already substantial.

(Galea et al., 2011) conducted cultural studies of evacuation behavior in Izmir, Türkiye, revealing that mixed-language signage and cultural hesitancy to evacuate without confirmation can add critical seconds to departure times. These findings highlight the importance of culturally tailored evacuation strategies and communication systems in diverse urban settings.

(Larsson et al., 2021) investigated the impact of crowd composition on egress performance, demonstrating that the presence of elderly or mobility-impaired individuals can alter evacuation times by up to 25% under identical geometries. This research highlights the importance of considering demographic diversity in evacuation planning and simulation, particularly in residential contexts where occupant capabilities vary widely.

2.2.2. Agent-Based Models

The development of computational evacuation models has transformed fire safety engineering by enabling the simulation of complex evacuation scenarios. (Helbing and Molnar, 1995) introduced the social force model, which conceptualizes pedestrians as particles subject to virtual forces—including social repulsion, attraction to goals, and boundary avoidance. This bottom-up approach captures emergent phenomena such as arching at doorways, stop-and-go waves, and lane formation in bidirectional flows.

Contemporary agent-based platforms like Pathfinder and buildingEXODUS have extended these modeling techniques to incorporate discrete spatial geometries, detailed stairwell representations, and demographic heterogeneity among agents (Thunderhead Engineering, 2024; Galea et al., 2017). These enhancements allow for more realistic simulations of evacuation scenarios by considering factors such as physical constraints of the built environment, age-based mobility variations, and behavioral differences under emergency conditions.

(Chen et al., 2021) reviewed evacuation simulation in indoor emergency situations. (Chen and Zhan, 2008) studied the relative effectiveness of simultaneous and staged evacuation strategies under four levels of population. Under low-density, free-flow conditions the simultaneous evacuation strategy yielded the shortest total clearance time, while at high densities on grid networks staged strategies alternating non-adjacent zones significantly reduced evacuation time.

(Kaur and Kaur, 2022) developed a multi-agent-based evacuation planning framework for disaster management, integrating both environmental and behavioral factors into a unified simulation model. Their approach enables more accurate prediction of evacuation patterns under various emergency scenarios, supporting more effective disaster preparedness planning at both building and urban scales.

2.2.3. Queuing and Environmental Conditions

The proliferation of high-rise buildings introduces unique vulnerabilities—vertical fire spread, stacked occupancy, and prolonged evacuation times—that differ markedly from low-rise contexts. The global high-rise boom, exemplified by developments in cities such as Istanbul, Hong Kong, Dubai, and Shanghai, has transformed fire risk landscapes (Qu et al., 2021). Comparative studies of ultra-tall buildings highlight that increased story counts exacerbate stairwell smoke infiltration alongside prolonged evacuation travel times due to queuing effects (Jodi et al., 2023). In the City of Istanbul, zoning policies since 2000 have encouraged vertical growth along specific peripheral corridors, yielding over 1,160 high-rise residential buildings exceeding 15 stories by 2020 (Jodi et al., 2023).

(Togawa, 1976) established critical density thresholds for pedestrian movement, observing that flow rates decreased significantly at densities above 1 person/m², recommending an assumed flow rate of 26 persons/min/1.1m of exit width for stair evacuations. This work identified the phenomenon of "crush conditions" that emerge at densities approaching 4 persons/m².

More recent research by (Harding et al., 2008) has further characterized these crush conditions, demonstrating how excessive densities (>3.8–4.0 persons/m²) can sharply reduce flow efficiency and create potentially fatal conditions through compression and trampling. (Kunwar et al., 2016) applied queueing theory to evacuation contexts, providing mathematical frameworks for analyzing situations where demand exceeds evacuation capacity, a common occurrence in high-rise building stairwells.

(Hopkin et al., 2019) investigated design fire characteristics for probabilistic assessments of dwellings, analyzing the Home Office Dwelling Fires Dataset to derive statistical distributions for key fire parameters such as fire damage area, heat release rate, and fire growth rate. Their work established that both RHR and fire growth rate follow lognormal distributions, though with different parameters than those typically assumed in prescriptive codes and guidance documents.

(Dundar and Selamet, 2023) examined fire load and fire growth characteristics in modern high-rise buildings, conducting surveys of residential furnishing arrangements and combustible contents to establish more accurate fire scenario parameters. Their work revealed significant variations in contemporary dwelling fire loads compared to historical assumptions, with implications for both evacuation planning and structural fire resistance design.

(Serteser and Karadağ, 2018) demonstrate how coupling CFD analysis with targeted architectural modifications can turn environmental-hazard insights into practical design fixes, where CFD-based fire and smoke predictions will inform adaptive interior features that improve tenability and evacuation. Their performance-driven method validates using simulation-led design iterations to align safety objectives with architectural intent.

(Spearpoint and Hopkin, 2020) studied temporal patterns in dwelling fires, analyzing the time of day and room of origin for residential fire incidents. Their findings demonstrated that kitchen fires predominate regardless of dwelling type while temporal distributions showed distinct patterns related to human activity cycles. These insights inform both prevention strategies and emergency response planning by identifying when and where residential fires are most likely to occur.

The impact of smoke on evacuation capacity represents a critical consideration in high-rise fire scenarios. (Jin and Yamada, 1985) established fundamental relationships between smoke density and human movement speed, demonstrating that at extinction

coefficients of 0.5 m^{-1} (a moderate smoke condition), walking speeds typically reduce to approximately 40% of normal rates. These findings have been incorporated into contemporary evacuation models through mobility degradation factors that reflect the physiological and psychological impacts of smoke exposure during egress (Jodi et al., 2023).

2.3. Emergency Response

Population density significantly influences both fire occurrence probability and potential casualties. (Cheng and Hadjisophocleous, 2011) found strong correlations between urban population density and fire ignition rates, with higher densities typically associated with increased fire frequency. (Corcoran et al., 2011) demonstrated that socioeconomic factors combined with population density account for significant variance in fire incident rates, highlighting the importance of incorporating demographic data into fire risk models.

(Okabe et al., 2008) employed six types of Voronoi, also known as Thiessen diagrams, to identify zones of inadequate coverage. These polygons create a partition where each polygon contains exactly one generating point (fire station), and any location within a polygon is closer to its generating point than to any other station, making them valuable for analyzing theoretical response territories and identifying potential service gaps.

The effectiveness of fire department response is a critical determinant of fire outcomes, particularly in high-rise buildings where self-evacuation may be challenging or incomplete. (National Fire Protection Association, 2020) establishes benchmark response times for first-due arrival (4 minutes) and full alarm assembly (8 minutes), providing standardized targets for municipal fire brigade planning and deployment.

(Challands, 2010) investigated relationships between fire brigade response time and fire outcomes, demonstrating strong correlations between arrival delays and fire severity,

property damage, and casualty rates. His work established quantitative relationships between response time variables and fire consequences, providing an empirical basis for emergency service planning and optimization.

Traffic flow characteristics have been identified as critical determinants of emergency response effectiveness (Jodi et al., 2023). (Spearpoint and Hopkin, 2020) found significant variations in response capabilities between weekday and weekend periods, and between different times of day. Using eight years of West Midlands fire brigade incident records, (Hopkin et al., 2020) showed that response capability varies systematically with the temporal distribution of incidents: call volumes are lowest between 03:00 and 11:00, rise through the afternoon, and peak on weekend evenings when kitchen fires are most prevalent.

(Sarreshtehdari and Khorasani, 2022) examined post-earthquake emergency response times to fire ignition locations, highlighting how infrastructure damage and traffic disruptions following seismic events can significantly impair fire brigade mobility. Their work emphasized the need for integrated planning that considers cascading hazards and their combined effects on emergency response capabilities.

Network robustness and redundancy are increasingly recognized as essential elements of resilient emergency response systems. (Scott et al., 2006) introduced the Network Robustness Index (NRI) to assess transportation network resilience under component failures, demonstrating how network topology affects system-wide performance during disruptions. Their analysis showed that highly centralized networks typically exhibit greater vulnerability to targeted disruptions, supporting the case for redundant access routes to high-risk areas.

(Koc et al., 2020) developed an integrated resilience assessment framework developed by addresses urban transportation network disruptions through a detailed structure-specific modeling approach. The method couples high-resolution, metropolis-scale travel demand modeling with hazard characterization and infrastructure damage

assessments to evaluate the impacts of disruptions comprehensively. By integrating real socioeconomic data into traffic simulations, the framework assesses network functionality under degraded conditions, quantifies the socioeconomic impacts through advanced regional economic analyses, and evaluates transportation disruptions across component-level vulnerabilities, network-level reconfigurations, and regional economic outcomes.

The spatial distribution of fire stations relative to high-risk areas is a fundamental consideration in urban fire protection planning. (Nyimbili and Erden, 2020) applied multi-criteria decision analysis using the Analytical Hierarchy Process (AHP) to optimize fire station locations in Istanbul, integrating geospatial data on population density, building characteristics, and transportation networks. Their work demonstrated the value of evidence-based approaches to emergency service siting decisions, particularly in complex urban environments with varied risk profiles.

(Tong and Murray, 2012) advanced spatial optimization methodologies for emergency service location planning, developing mathematical frameworks for maximizing coverage efficiency while minimizing response times across heterogeneous urban landscapes. Their location-allocation models provide valuable tools for optimizing fire station placement and resource distribution, supporting more efficient and equitable emergency service provision.

(Urbina et al., 2023) applied GIS-based methods to assess the vulnerability of critical infrastructure networks to fire hazards, integrating spatial patterns of risk exposure with network connectivity analysis. Their study highlighted the importance of considering environmental hazards alongside infrastructure topology when evaluating network resilience and planning emergency response strategies.

The development of decision support tools that bridge technical analysis and practical application represents an emerging frontier in urban fire safety. (Akashah et al., 2020) investigated factors affecting the adoption of emergency evacuation strategies in

high-rise office buildings, identifying technological, organizational, and human factors that influence implementation success. Their work highlights the importance of risk communication and decision support in emergency management systems, ensuring that technical capabilities align with operational realities and user needs.

2.4. Combined Fire Risk

Fire risk assessment has evolved from deterministic approaches to more sophisticated probabilistic methodologies that better account for uncertainties and complex interactions. (Hasofer et al., 2007) emphasized that conventional fire risk assessment (FRA) frameworks often produce single-value estimates rather than probability distributions, potentially leading to misleading conclusions and inadequate protective measures. This limitation has driven the development of more sophisticated probability-based approaches (Otay et al., 2025).

(Meacham et al., 2016) advanced the concept of building fire risk analysis by proposing a framework that integrates deterministic and probabilistic elements while considering both technical and socioeconomic factors. Their approach emphasizes the importance of stakeholder engagement, performance criteria definition, and uncertainty analysis in developing comprehensive risk assessment models that can support evidence-based decision-making in city-scale fire preparedness.

Recent research has expanded beyond individual building assessment to consider fire risk at urban and regional scales. (Lee et al., 2020) developed a comprehensive methodology for assessing fire severity using three complementary approaches: Analytical Hierarchy Process (AHP), big data analysis, and remote sensing. Their work identified six critical factors affecting fire severity: rescue response time, narrow road density, water-scarcity area density, building risk, hazardous materials' place density, and fire safety inspection-regulated premises density. (Nyimbili and Erden, 2020) also proposed the use of AHP to identify optimal locations for new fire stations, integrating multiple criteria including population density, building characteristics, and access to

transportation networks.

Recent literature also emphasizes that urban fires are not isolated incidents but are influenced by broader urban development patterns and network infrastructure vulnerabilities (Mandalapu et al., 2024). A combined fire risk is used in the present framework. This is defined as a joint event of the building-level fire incident (probabilistic evacuation time) and the inadequacy of the emergency response (time for firefighters to arrive). The actual fire risk occurs at the intersection of these two negative events.

To analyze the combined risk a framework is adopted which integrates building-level agent-based occupant evacuation model with city-wide GIS-based spatial analysis of fire incidents and fire stations. couples micro-level simulation of evacuation with macro-level spatial analysis, ensuring that evacuation demand (time required for occupants to reach safety) is systematically compared against emergency response supply (time for firefighters to arrive). (Estevez et al., 2016) highlighted the increasing availability of data on risk variables that can be harnessed and adapted to different situations, supporting more effective community-level risk management and disaster response monitoring.

3. METHODOLOGY

This chapter presents the methodological framework for assessing fire risk and emergency response capacity for high-rise residential buildings at a city scale. The framework integrates building-level evacuation dynamics with urban-scale emergency response analysis through a systematic multi-level approach. By combining micro-scale agent-based modeling with macro-scale geospatial analysis, the methodology provides a comprehensive foundation for understanding both individual building vulnerability and system-wide resilience of a city's emergency response.

The methodology is structured around four interconnected analytical components: (1) occupant evacuation and hazard modeling, (2) fire emergency response analysis, (3) city-scale risk assessment, and (4) emergency response resource allocation optimization. Each component employs specialized analytical tools while maintaining interoperability. This integrated approach enables the translation of building-specific evacuation parameters into actionable insights for municipal resource allocation and emergency planning.

The following sections detail the analytical procedures employed in this study. Section 3.1 outlines the research framework, contextualizing the methodology within established disaster management principles. Section 3.2 describes the agent-based modeling approach used to simulate occupant evacuation under various scenarios. Section 3.3 presents probabilistic analysis of fire emergency response times, incorporating network constraints and operational uncertainties. Section 3.4 details the geospatial techniques used to evaluate city-scale vulnerability and optimize resource allocation. This chapter provides the foundation for the empirical analyses presented in Chapters 5 and 6.

3.1. Research Framework

The present study employs a research methodology aligned with the internationally recognized disaster management framework (Federal Emergency Management Agency, 1996), which generally encompass four interrelated phases: mitigation, preparedness, response, and recovery. This is illustrated in Figure 3.1. Recognizing that these dimensions operate as interconnected quadrants rather than isolated stages, the methodology is structured to capture the dynamic, cyclical essence of disaster management while providing a comprehensive analysis of fire risk and emergency services within an urban setting research adopts a risk assessment framework.

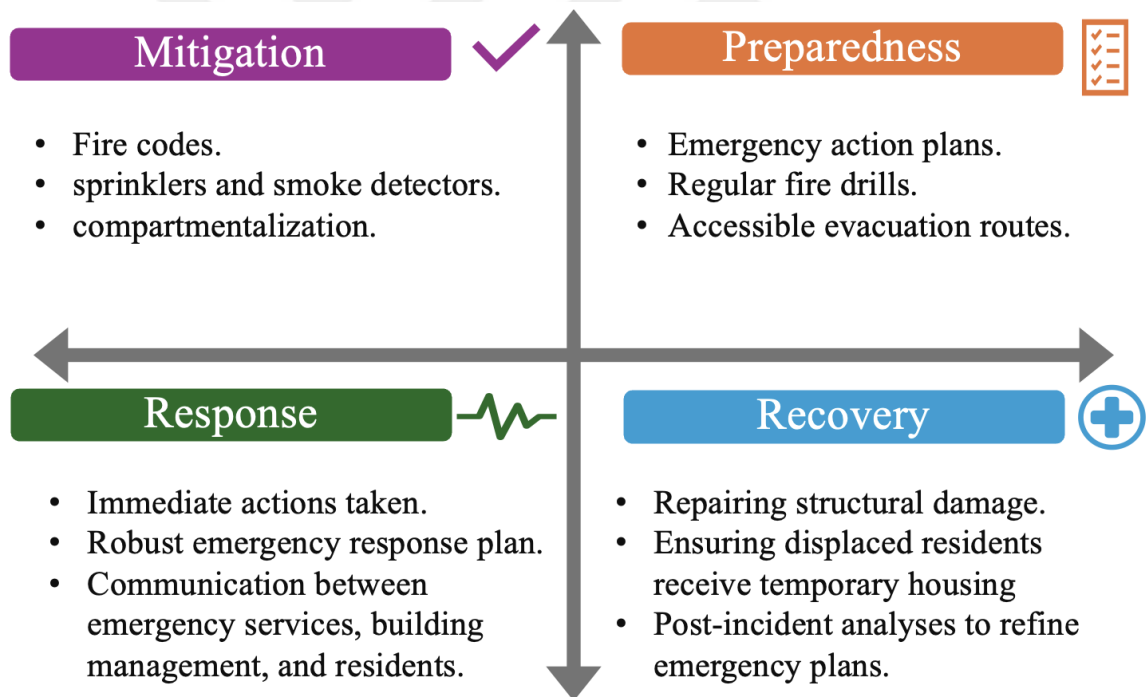


Figure 3.1. A 4-Stage Disaster Management Model.

In the mitigation phase, the research focuses on identifying potential hazards that could lead to severe fire incidents in urban settings. Data are collected from multiple sources, including building records, city infrastructure databases, and historical fire incidents. However, our focus is on the preparedness and response phases for urban fire disasters, wherein proactive analysis can enhance city-scale resilience. The goal is to

highlight critical risk factors and propose infrastructural and policy recommendations that could diminish the overall fire risk at the city scale.

Response phase is addressed by modeling real-time reaction capabilities to fire outbreaks. To address the recovery phase, the research methodology examines post-incident outcomes to assess the efficacy of the overall emergency management system. The study uses surveys, case studies, and statistical analyses to evaluate the recovery process, identify bottlenecks, and measure the long-term resilience of affected communities. Insights from this phase are instrumental in informing policy revisions and developing more robust systems for future disaster mitigation and recovery.

The framework integrates micro-level simulation of evacuation with macro-level spatial analysis, ensuring that evacuation demand (time required for occupants to reach safety) is systematically compared against emergency response supply (time for firefighters to arrive). The timeline for the two processes is shown in Figure 3.2. At the building scale, an agent-based evacuation model is used to simulate how occupants evacuate under various conditions, accounting for human behavior and fire-induced hazards. At the city scale, a GIS network model evaluates emergency vehicle travel times across the city's road network and identifies coverage gaps.

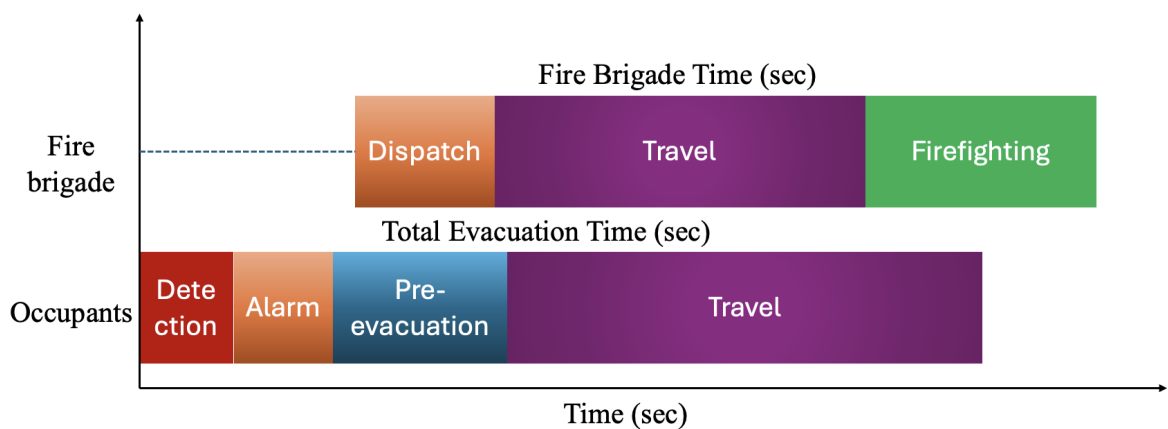


Figure 3.2. Evacuation-Response Timeline.

Regression analysis is used to extrapolate the simulation data to real-world buildings. As Figure 3.3 demonstrates, the outcome is a set of metrics – notably a Vulnerability Index per building and a Risk Index per district or spatial region – that quantify fire risk in terms of the likelihood that evacuation would be completed before fire brigade arrival, under worst-case conditions. Monte Carlo probabilistic sampling techniques are employed to incorporate uncertainty in external factors (such as time and location of incidents as well as traffic congestion). These metrics support evidence-based decision-making for resource allocation, such as identifying high-risk buildings and optimal locations for new fire stations.

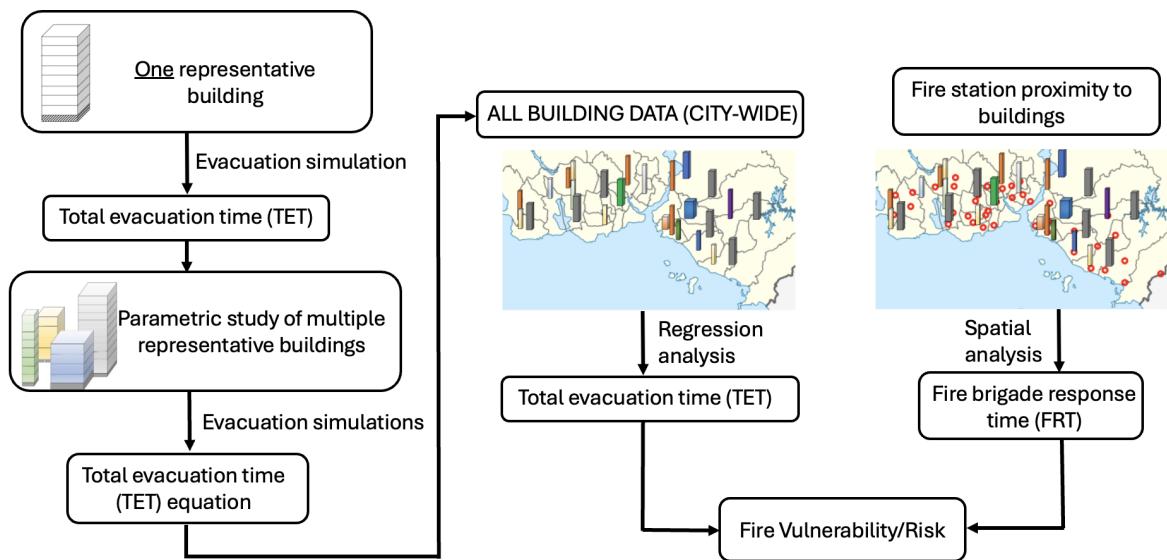


Figure 3.3. Summary of the Methodology for Assessing City-Scale Fire Risk.

3.2. Occupant Evacuation Model

The expressions in fundamental movement calculations relate primarily to the effective width (i.e., usable clear width accounting for body sway) of the egress component as well as the density, speed and flow characteristics of the evacuating population. The first assumption in the hydraulic model is the relationship between speed and density.

For an individual or a population group, the velocity at which evacuees move is a function of the degree of crowdedness in an evacuation route. The relationship between speed and density is given by

$$S = f(D) \quad (3.1)$$

which can be expressed in linear form as

$$S = k - akD \quad (3.2)$$

where S represents the speed of evacuation, D is the population density within the evacuation component, and a and k are proportionality constants.

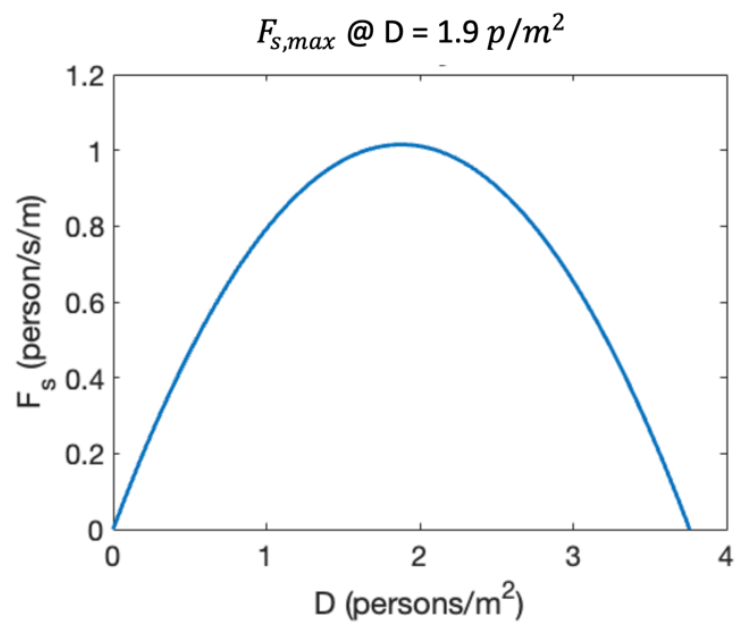
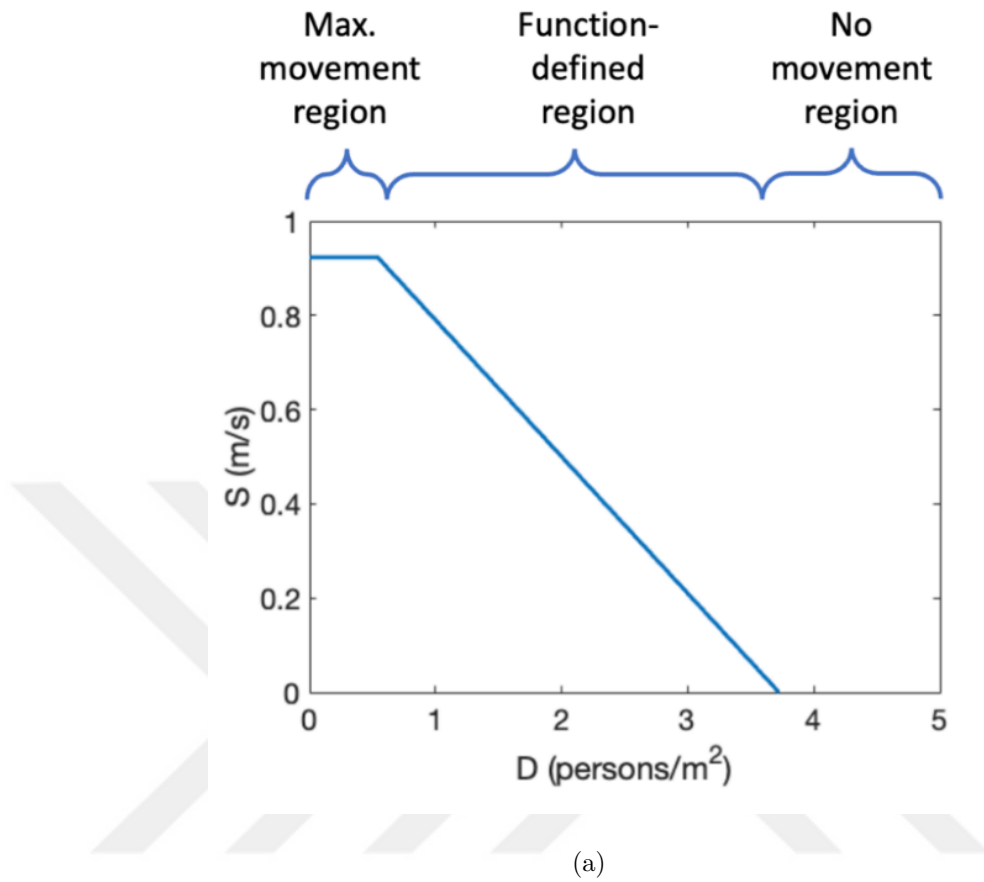
For the stair component, Equation (3.2) is plotted and shown in Figure 3.4. From the figure, three fundamental laws of evacuation movement can be deduced:

- (i) At a very low density, evacuees move at their normal speeds.
- (ii) At a very high density, evacuee movement is completely inhibited.
- (iii) Between these two extreme values lie some thresholds after which (in case of 1) or before which (in case of 2) which can be described by a specific type of function.

The speed determined from the Equation (3.2) is along the line of movement. On the stairs and landing, the speed is adjusted based on the tread width and height. The speed on the stairs is proportional to the square root of the ratio of the tread width and height as given by (Gwynne and Rosenbaum, 2016), such that

$$S \propto \sqrt{\frac{G}{R}} \quad (3.3)$$

where G is the stair tread width and R is the stair tread height.



(b)

Figure 3.4. Stair Evacuation Constraints: (a) Speed-density relationship and (b) Flow rate-density relationship.

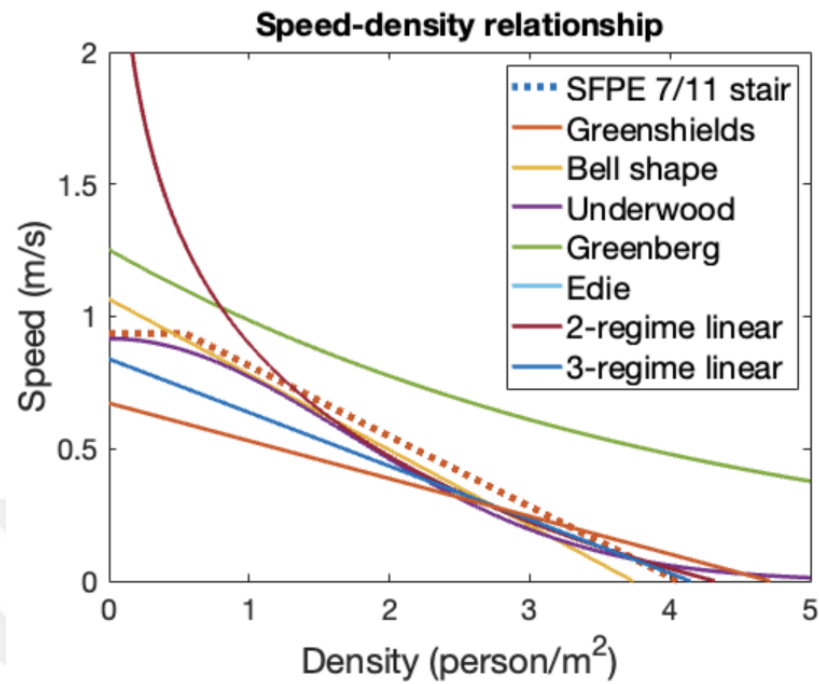
If the density increases significantly, a phenomenon known as crush condition occurs. This is the cause of stampede (Harding et al., 2008). Hence there is a limit on the achievable flow rate which assigns a constraint limit on the movement of the evacuees. Table 3.1 details the threshold values at which these conditions occur.

Table 3.1. Threshold of movement variables.

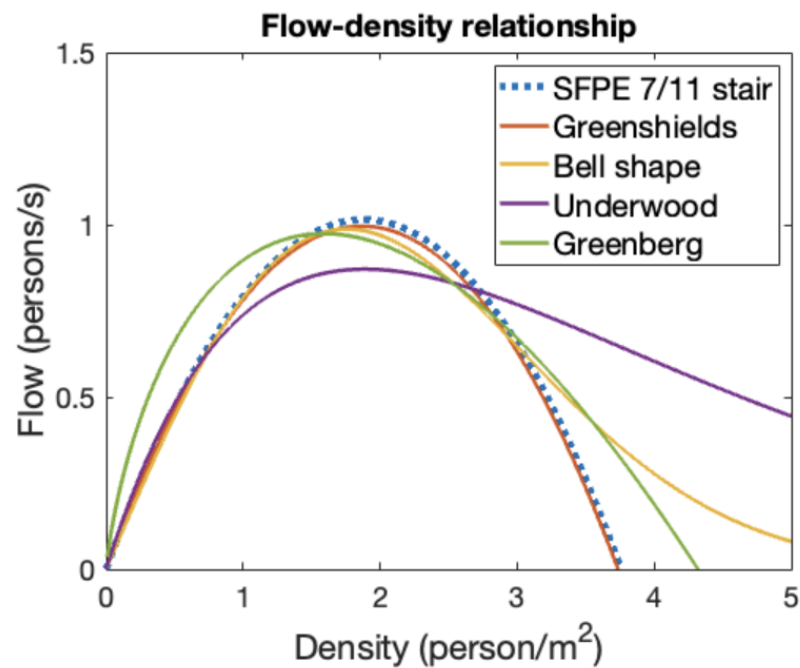
Floor occupant density	Threshold value
Lower speed restriction	0.54 persons/m ²
Upper speed restriction	3.8 persons/m ²
crush conditions	~ 4 persons/m ²
D @ maximum achievable flow rate	1.9 persons/m ²

Among the pedestrian movement models mentioned in chapter 2, Figure 3.5 compares the standard literature models to show the differences in the peak of the resulting flow–density curves, meaning the predicted critical density and maximum corridor capacity vary by formulation. The SFPE model used by buildingEXODUS is conservative for the stair evacuation component.

In the agent-based evacuation analysis software buildingEXODUS, detailed floor plan geometries for a total of a representative building will be made. As the schematic in Figure 3.3 indicates, by replicating the same floor plan geometries to 7 different number of building heights (15, 20, 25, 30, 35, 40 and 45 floors), the simulation results of these 315 representative buildings can then be used to find correlations between the TET of any building with the aforementioned building floor area and height (number of floors) data to estimate the TETs of all the city’s high rise residential buildings.



(a)



(b)

Figure 3.5. Pedestrian movement models: (a) Speed-density relationship models and (b) Flow rate-density relationship models for occupant evacuation.

The process by which a software is independently evaluated for reliability is termed Verification and Validation (V&V). The main guidance for V&V of evacuation models

provided by the International Maritime Organization (IMO) mainly for ships are used for evacuation models of other kinds of structures. The information in which a software is compared against can be in the form of qualitative expectations or quantitative experiment, or a routine checking of software sub-components and their inherent assumptions. Behavioral uncertainties are acknowledged, and standard procedures are used in the validation process. The EXODUS suite of software has undergone V&V evaluations and have been verified (Galea et al., 2017). Like many evacuation models, the software has been validated against fire drills, past experiments, other models and by third party (Kuligowski, 2016).

3.2.1. Building Geometry Sub-Model

The buildingEXODUS engine discretizes interior space into a rectangular lattice of nodes ($0.5 \text{ m} \times 0.5 \text{ m}$) connected by arcs. Each node may hold at most one agent at any instant, and each arc imposes a travel cost corresponding to 0.5 m of physical displacement. The discretization therefore guarantees a maximum local density of $4 \text{ persons} \cdot \text{m}^{-2}$ while maintaining computational tractability for large populations. Each node carries a set of attributes that specify its terrain class, environmental conditions, and spatial position. These attributes matter because they directly affect any agent moving across the node. Every node shares a standard set of core attributes, while those serving special functions include additional special-purpose attributes. Core attributes are summarized in Figure 3.6.

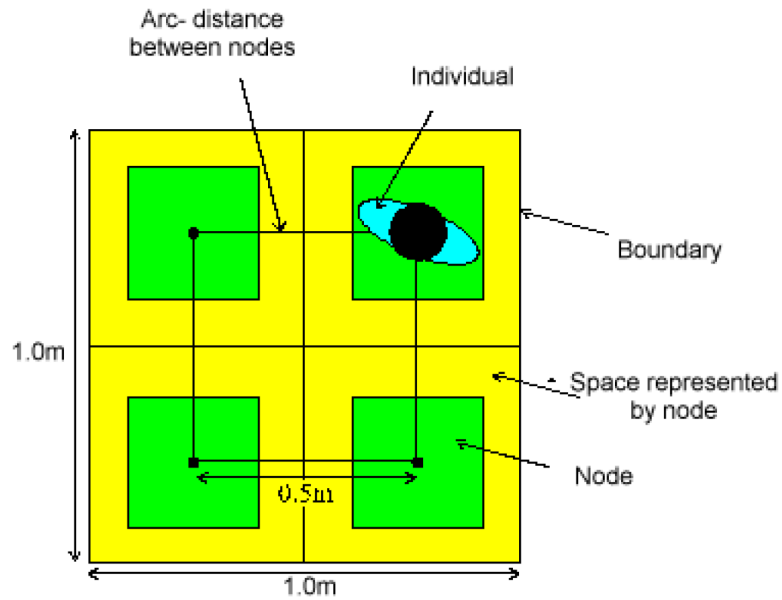


Figure 3.6. Node representation of a 1m x 1m area enclosure in buildingEXODUS (Galea et al., 2017).

Each node carries a set of attributes that specify its terrain class, environmental conditions, and spatial position. These attributes directly affect any agent moving across the node. Every node shares a standard set of core attributes, while those serving special functions include additional special-purpose attributes. Core attributes include node type (internal node, exit node, stair node, or landing node), potential, i.e., distance to the nearest exit (measured in nodes) and environmental conditions (temperature, smoke density, or toxicity).

Several floor plans were first chosen to carry out preliminary studies on the effect of floor plan on the total evacuation time with occupants placed at different locations of the building. The evacuation simulations were performed assuming a random placement of occupants on each floor. Figure 3.7 shows that the exit time is not significantly affected by these category of buildings. This suggests that the horizontal evacuation to the stairs has minor effects on the total evacuation time.

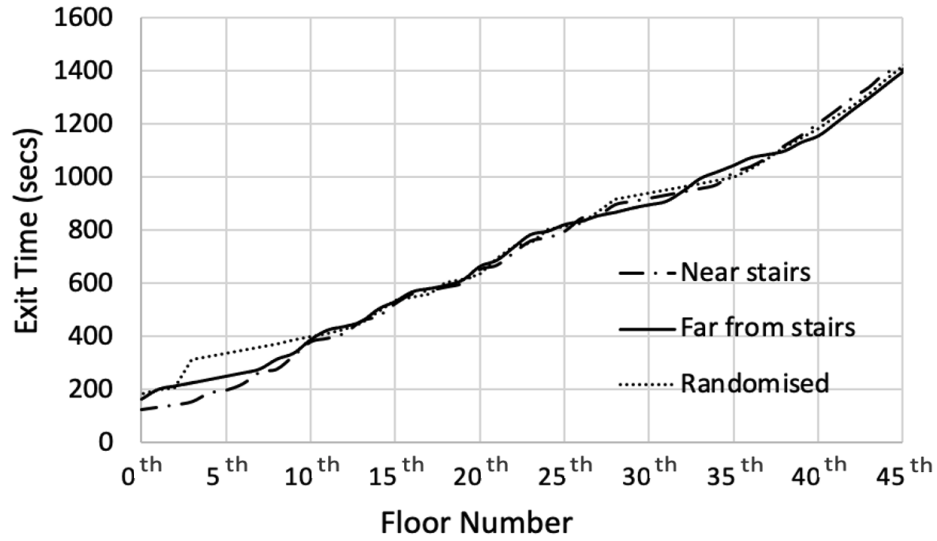


Figure 3.7. Comparison of exit times of occupants at different starting locations on a floor plan.

As a result, one building floor plan is chosen as a representative floor plan to carry out parametric simulation building. Floor characteristics represent the standard configuration for high-rise residential buildings in Istanbul, as derived from the representative buildings selected for preliminary modeling. The values conform to Turkish building regulations (BYKHY, 2007) and provide a consistent basis for comparative analysis across different building heights. The floor plan of the representative building is shown in Figure 3.8. Figure 3.9 shows the building EXODUS fine-network node-model of this floor plan. Table 3.2 lists other geometric characteristics of the building. Table 3.3 describes the representative building.

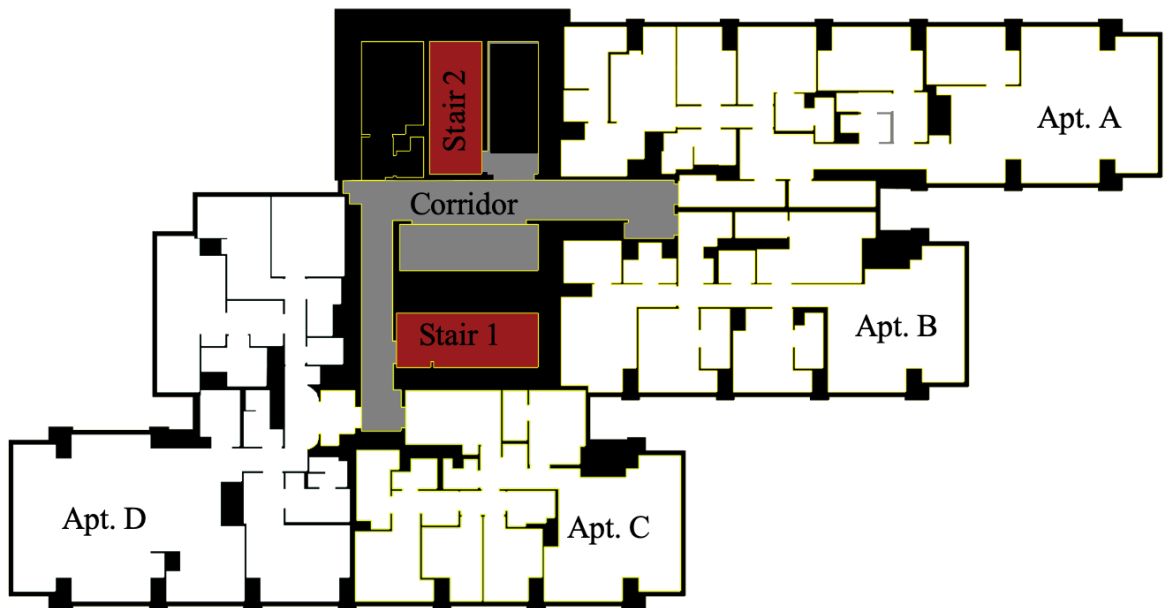


Figure 3.8. Floor layout of the representative high-rise residential buildings (b) locations of the buildings with the 20 real floor plans in the City of Istanbul.

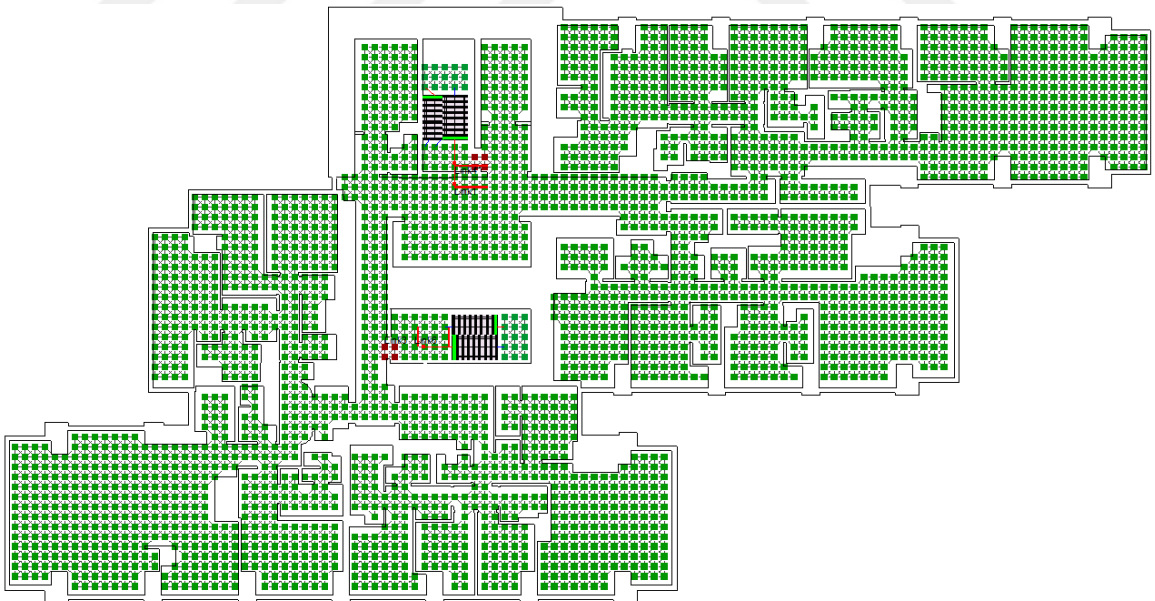


Figure 3.9. buildingEXODUS model of floor layout of the representative high-rise residential buildings.

Table 3.2. Geometric characteristics of a representative high-rise residential building.

Building Characteristic	Value
Occupant Floor Factor	20 $m^2/person$
Nominal stair width	1220 mm (two lanes)
Height between floors	3.85 m
Stair riser height	214 mm
Stair tread depth	281 mm
Number of risers per floor	9 stair risers per floor
Stair landing dimension	1.5 m by 2.5 m
Handrail intrusion	0.87 m (0.1 m width)

Table 3.3. Total useable area and occupants of model tower compartments.

Compartment	Area (m^2)	Number of Occupants
A	250.6	13
B	175.5	9
C	159.9	8
D	252.9	13
Total	838.9	43

3.2.2. Occupant Behavior Sub-Model

The characteristics of individual occupants have been carefully chosen to reflect the demographic of the Turkish population (Jodi et al., 2023). Table 3.4 gives the characteristics of the evacuating population. As Table 3.4 shows, the speed of the population is determined by the age and gender of the individual in within the population. On free space on the floor plan, speed is assumed to be constant across the population when there is no queuing. However, on the stairs, the speed varies with age and gender. Other characteristics are categorized by gender only.

Table 3.4. Occupant characteristics and walking speeds.

Occupant Characteristics			Walking Speed on Stairs (m/s)		
	Males	Females	Age group	Males	Females
< 30 years	20%	20%	< 30 years	1.01	0.755
30–50 years	20%	20%	30–50 years	0.86	0.665
> 50 years	10%	10%	> 50 years	0.67	0.595
Height	1.65–1.85 m	1.55–1.75 m	Walking Speed in Free Space (m/s)		
Agility	4–6	5–7	All ages	1.5	1.5
Drive	9–11	11–13	Walking speed on Stair Landings (m/s)		
Patience	160–200 sec.	180–220 sec.	All ages	1.35	1.35
Pre-evacuation response time	lognormal	lognormal			

At every 1/12-s simulation clock tick, each agent executes the following behaviors:

- (i) Perception: read node terrain, local hazard set, neighboring potentials.
- (ii) Behavior rule evaluation: decide desired arc, speed regime, and evasive action (overtake, side-step).
- (iii) Conflict resolution: if multiple agents claim the same node, the one with highest *Drive* wins; ties resolved pseudo-randomly.
- (iv) Motion: update position; accumulate exit time and travel distance.

In the Table 3.4, the agility attribute refers to an occupant’s physical ability in tackling obstacles with possible range set between 0 and 7 (Galea et al., 2017). Drive is the measure of the assertiveness of the occupant used as a basis in conflict resolution at a location. Patience is a measure of the amount of time an occupant is prepared to wait before considering or attempting an alternative action such as moving away from queue. The occupant population demographic is grouped according to age with a 1:1 male to female ratio (Oven and Cakici, 2009). Although the pre-evacuation delay in different populations can have a different mean and standard deviation, it generally follows a log-normal distribution for different countries (Galea et al., 2011; Purser and Bensilum,

2001). The distribution range applied in the evacuation simulations is between 11 seconds and 181 seconds with a mean of $\mu = 42 \text{ seconds}$ and a standard deviation of $\sigma = 2 \text{ seconds}$ as shown in Figure 3.10.

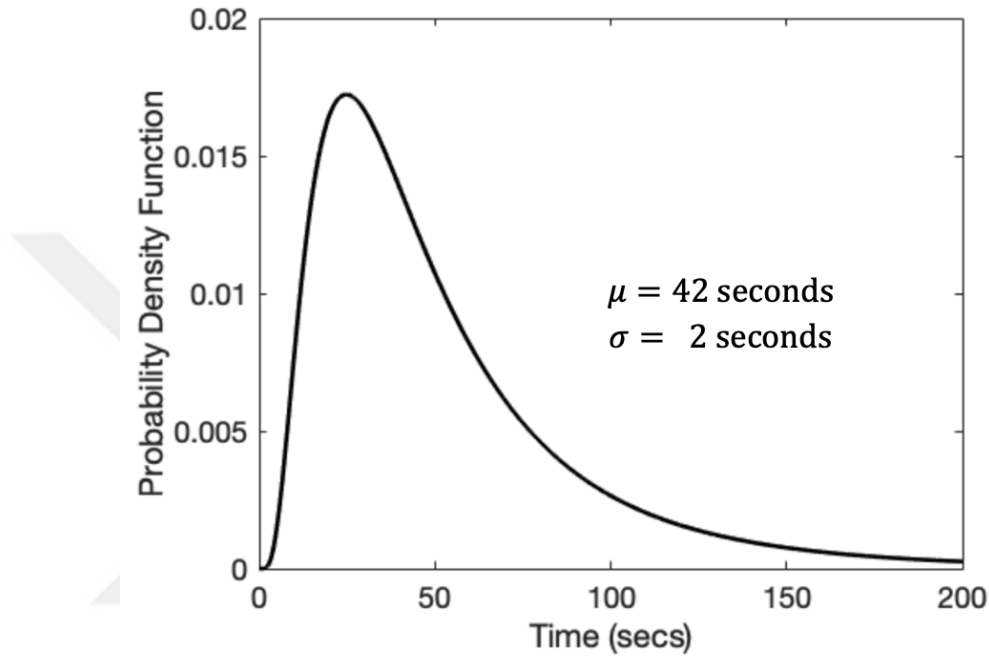


Figure 3.10. Distribution of pre-evacuation time (Galea et al., 2011).

3.2.3. Fire Hazard Sub-Model

The movement of the occupants is generally assumed to be non-impaired. However, smoke and irritant gases produced by fire may impair occupant visibility thereby affecting their choice of exit or slowing them down. This further evacuation delay from a building base evacuation time further exposes more occupants to higher risk. Because the fire simulation variables are input parameters for the occupant evacuation analysis, the analytical procedure with which the values are obtained is given in this section.

When evacuees encounter smoke during evacuation, their walking speed reduces depending on the extinction coefficient (K). The extinction coefficient and the optical density are related by $\log_{10} e^1$ which can also be evaluated by

The optical density and extinction coefficient are related by

$$\text{Optical Density} = \frac{K}{2.3} \quad (3.4)$$

where K is the extinction coefficient.

The occupant speed is capped by the relationship

$$v = \text{Speed}_{\max} \times \text{Mobility} \quad (3.5)$$

where $\text{Speed}_{\max}$ comes from Table 3.4 and Mobility is determined from Figure 3.11.

When crowding exceeds $3.8 \text{ persons} \cdot \text{m}^{-2}$, the social-force component introduces a crush penalty reducing effective flow by up to 40% (Togawa threshold). The occupant movement speed can be hindered due to the smoke produced by fire using a mobility degradation factor. The mobility degradation begins effect at an extinction coefficient of $0.1 \frac{1}{m}$ and no further change in speed is assumed for the extinction coefficient larger than $0.5 \frac{1}{m}$. This is the point at which the occupant is forced to exhibit crawling behavior at which the movement speed is diminished by more than 60% (Jin and Yamada, 1985).

The smoke transport calculation of a fire is performed in a Fire Dynamics Simulator (FDS) with polyurethane as fuel. The FDS model is created in PyroSim (Thunderhead Engineering, 2024). The fire scenario is assumed to take place on the 6th floor as shown in Figure 3.12. This assumption is based on an NFPA survey of 15,400 high-rise building fires in the United States between 2007-2011 (Hall, 2013). Also, since living rooms are generally the closest regions to the apartment doors and hence have the easiest means of spreading to the corridors and stairs, the design fire is created in the living room.

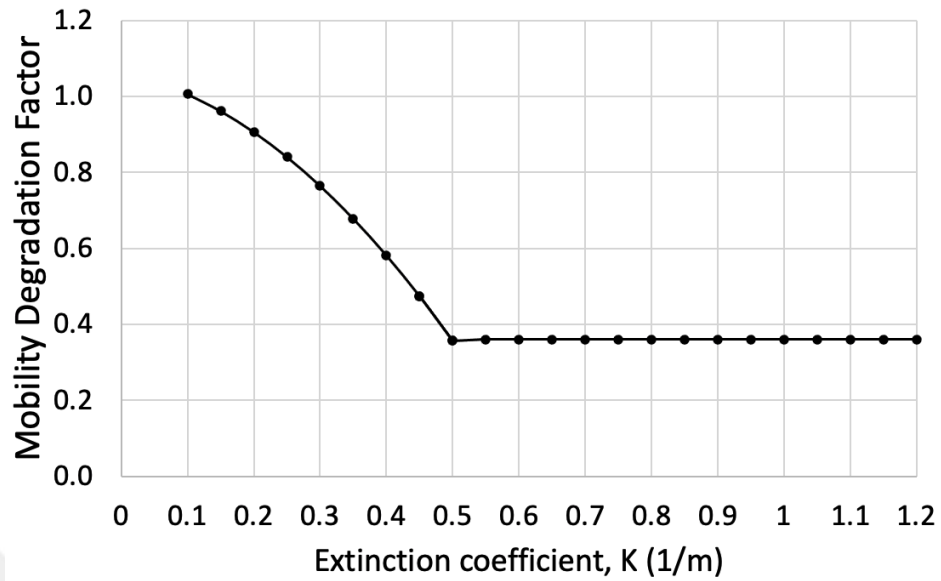


Figure 3.11. Mobility degradation factor adapted from (Jin and Yamada, 1985).

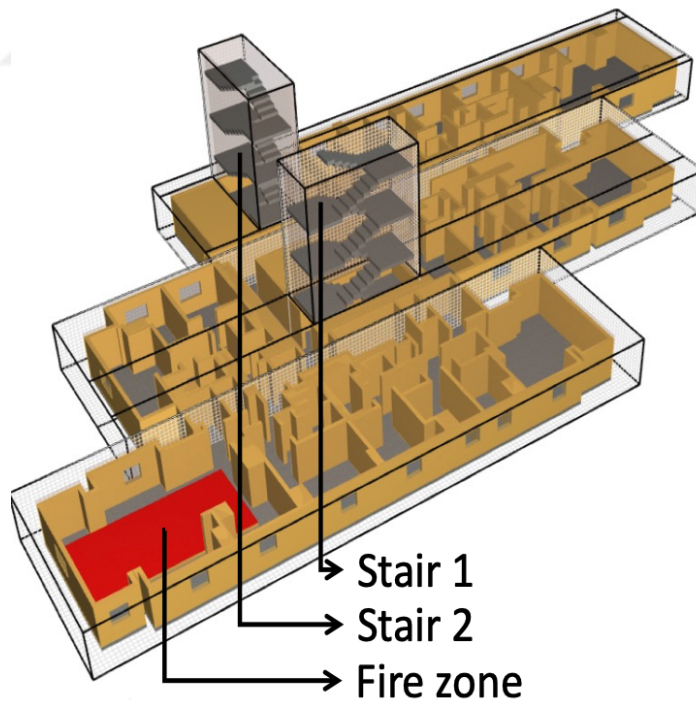


Figure 3.12. Fire floor (6th) in FDS model and 3 critical locations where the gas temperature is measured (at $h = 1.75$ m from floor).

As seen in Figure 3.13, based on a fuel load survey of high-rise residential buildings (Dundar and Selamet, 2023), the average peak RHR for different types of apartments

is 12.94 MW with an average 5,523 MJ energy release, about the same as a 3+1 (3 bedrooms and 1 living room) apartment with a 47 m² area. The RHR density is also in accordance with Eurocode 1 provisions of 250 kW/m² for dwellings (Dundar and Selamet, 2023). In order to take account of the worst-case fire scenario, the FDS simulations were run with fully open stairway doors and the smoke and heat were allowed to move through to two upper floor levels.

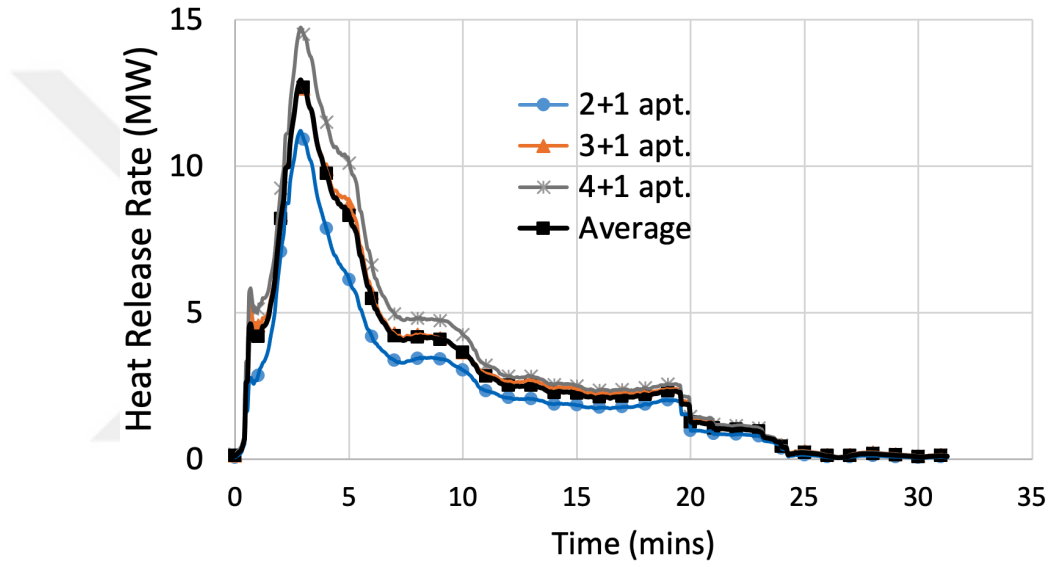


Figure 3.13. Heat release rate of a typical living room fire.

A mesh sensitivity analysis for the FDS model was conducted for 25 cm and 15 cm cell sizes. To estimate the mesh size, the characteristic length scale of the fire is calculated using the characteristic fire diameter equation,

$$D^* = \left(\frac{Q}{\rho_{\infty} c_p T_{\infty} \sqrt{g}} \right)^{2/5} \quad (3.6)$$

where D^* is the characteristic fire diameter in m, Q is the peak heat release rate (RHR) in kW, ρ_{∞} is ambient air density in kg/m³, c_p is the heat capacity of air under constant pressure in kJ/kg.K, T_{∞} is the ambient temperature in Kelvin, and g is the gravitational acceleration in m/s².

3.2.4. Evacuation Time-History Analysis

The evacuation time-history analysis converts buildingEXODUS simulation outputs into a continuous record of occupant evacuation over time. The exit time function is obtained by performing computational operations on the buildingEXODUS output. The evacuation time-history analysis begins by importing each occupant's recorded exit time from the Exodus simulation results and discretizing the timeline into uniform intervals.

First, the simulation data are imported and sorted by floor evacuation time. Let $E(t)$ denote the cumulative number of occupants who have reached a designated safe zone (building exit in this case) by time t . The cumulative number of occupants evacuated by time t is expressed as

$$E(t) = \sum_{i=1}^N H(t - t_i) \quad \forall \quad H(x) \begin{cases} 1, & x \geq 0 \\ 0, & x < 0 \end{cases} \quad (3.7)$$

with t_i the exit time of occupant i , and N is the total occupant population.

For a floor-by-floor decomposition, if the building has F floors and N_f occupants on floor f , the cumulative number of occupants exited can similarly be defined as

$$E(t) = \sum_{f=1}^F E_f(t) \quad \text{where} \quad E_f(t) = \sum_{i=1}^{N_f} H(t - t_i^{(f)}) \quad (3.8)$$

This simple summation yields a step-wise evacuation curve which, when plotted against time, reveals the overall pace of evacuation. From this cumulative profile one obtains the evacuation flow rate, which represents the number of occupants exiting per unit time during the interval $[t_{k-1}, t_k]$:

$$q[k] = \frac{E[k] - E[k-1]}{\Delta t} \quad \text{for } k = 1, 2, \dots \quad (3.9)$$

Peaks in $q[k]$ indicate moments when the largest numbers of occupants pass through bottlenecks in stairwells or corridors.

The cumulative count at each time step is calculated as

$$E[k] = \sum_{i=1}^N \mathbf{1}(t_i \leq t_k) \quad (3.10)$$

where $\mathbf{1}(\cdot)$ is the indicator function. The floor clearance is illustrated by the schematic in Figure 3.14.

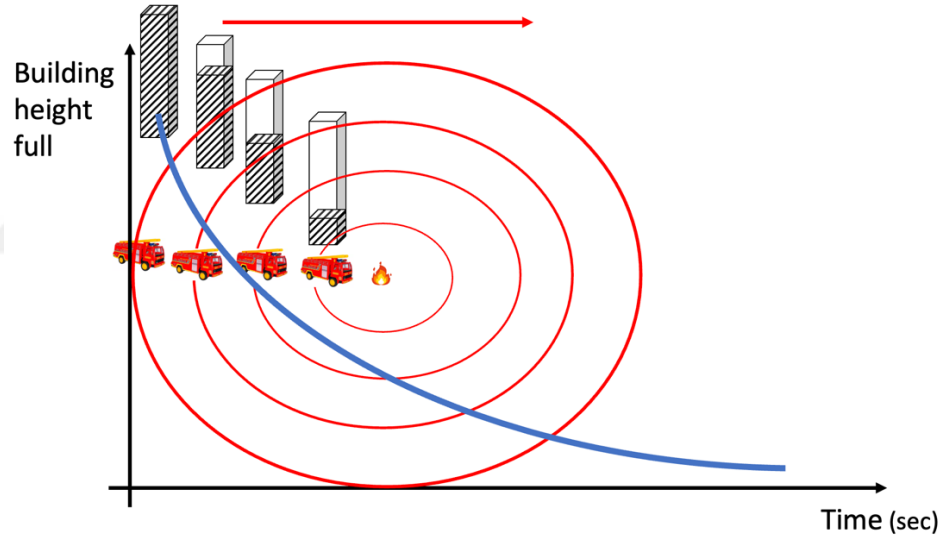


Figure 3.14. Schematic evacuation time-history of a typical high-rise building.

3.2.5. Regression Analysis of Occupant Evacuation Time

The regression model of total evacuation time of building occupants is specified as

$$\text{TET} = \beta_0 + \beta_1 F + \beta_2 D + \epsilon \quad (3.11)$$

where F is the number of floors, D is occupant density per floor, $\beta_0, \beta_1, \beta_2$ are regression coefficients and ϵ is a zero-mean perturbation term. Ordinary least squares estimation

is performed by minimizing the sum of squared residuals, which is expressed as

$$\sum_{i=1}^n \left(\text{TET}_i - \widehat{\text{TET}}_i \right)^2 \quad (3.12)$$

where TET_i is the observed evacuation time for scenario i and $\widehat{\text{TET}}_i$ is its prediction.

Model fit is quantified by the coefficient of determination, which measures the proportion of variance explained by the regression model:

$$R^2 = 1 - \frac{\sum_{i=1}^n \left(\text{TET}_i - \widehat{\text{TET}}_i \right)^2}{\sum_{i=1}^n \left(\text{TET}_i - \overline{\text{TET}} \right)^2} \quad (3.13)$$

where $\overline{\text{TET}}$ represents the mean of observed evacuation times.

The resulting empirical equation is then incorporated into the city-scale risk framework to compare evacuation completion against fire brigade arrival under diverse scenarios.

3.3. Fire Emergency Response Analysis

Fire brigade response time is composed of several components (Tómasson et al., 2008), including the turnout time from notification of the fire unit to leave for rescue operation and the travel time from leaving the fire station until arrival at the burning building. As with the required safe egress time of occupants, the fire detection time and notification time of the fire brigade are also influenced by technical solution and human intervention. Furthermore, the notification period of the fire brigade varies according to fire station capability.

The delay in fire brigade response time due to traffic as can be witnessed in many big cities is accounted for by considering congestion on the roads at the peak traffic period. The aim of a risk index in fire safety evaluation is to simplify decision-making by

combining multiple fire safety attributes into a single number which provides information about relative levels of safety. In the context of fire brigade intervention, an effective fire brigade intervention implies that the occupants can be saved by the facility before untenable fire conditions are reached in the building. In this study, the total evacuation time (TET) for each building is compared to the corresponding fire brigade response time (FRT).

3.3.1. Probabilistic Modeling of Response Time

Fire response operating time is defined as the interval during which the fire brigade mobilizes and travels to the scene, measured from the instant the emergency call is received until the moment the first firefighting unit arrives back from fire site when all tactical operations are complete. It can be decomposed into the components shown in Figure 3.15, which schematizes the sequence of operating intervals from initial fire ignition through to on-scene intervention and eventual return to back to the station.

This timeline is partitioned into three phases:

- (i) Unmitigated fire-growth time: the interval from ignition to the onset of suppressant action, comprising building evacuation and reflex delays.
- (ii) Fire department reflex time: spanning notification, turnout, and crew mobilization, up to arrival at the incident site.
- (iii) On-site activation time: the period between crew arrival and commencement of extinguishing operations, including pump hookup and safety checks.

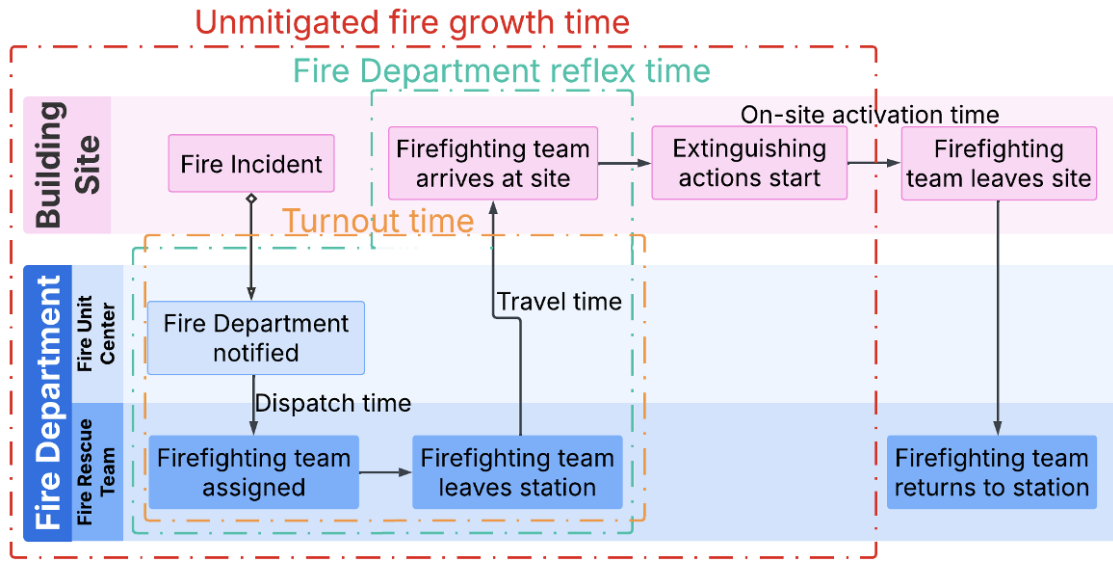


Figure 3.15. Operating time of Istanbul fire brigade response.

The operating time is the length of time from the moment the fire brigade is notified until the fire unit returns to the fire station. The operating time of fire brigade can be divided into separate components which can be connected to calculate the overall probability of fire suppression success (Hasofer et al., 2007). The total time from ignition until extinguishing actions start can be described as the unmitigated fire growth time. The turnout time is the length of time from the moment the fire brigade is notified until it leaves the fire station. The response time, also known as the fire department reflex time, is the length of time from the moment the fire brigade is notified until the unit is at the fire scene. It is the sum of the turnout time and the travel time.

A critical temporal threshold known as available safe egress time (ASET) is used to for PRA. ASET is characterized as the interval between fire ignition and the point at which conditions in the egress routes deteriorate to an untenable level. In contrast, the available safe egress time (RSET) is defined as the total time occupants require to complete the detection, alarm, pre-movement and travel phases and reach a place of safety. By comparing the realizations of the random variables TET (total evacuation time) and FRT (fire response time) against the common threshold, α , the Bayesian model quantifies the likelihood of successful evacuation and timely fire-brigade

intervention, and allows these risk estimates to be updated as new data become available.

Employing a probabilistic model rooted in Bayesian reasoning to estimate the combined risk of fire incidents leading to adverse outcomes treats evacuation time and response time as random variables, allowing us to quantify the likelihood of undesirable scenarios and update probabilities as new data becomes available. For a given building fire incident, let TET denote the total evacuation time and FRT denote the fire response time. We define two critical events using α as the ASET threshold:

- A : $\{TET > \alpha\}$ - evacuation exceeds safe time limit
- B : $\{FRT > \alpha\}$ - response exceeds safe time limit

Assuming statistical independence between evacuation and response processes, the combined risk is expressed as

$$R = P(A \cap B) = P(A) \times P(B) \quad (3.14)$$

This follows from conditional probability $P(A \cap B) = P(A | B) \cdot P(B)$ with independence assumption $P(A | B) = P(A)$.

The individual probabilities are estimated empirically through

$$\Pr(A = TET > \alpha) = \frac{n_A}{N} \quad (3.15)$$

and

$$\Pr(B = FRT > \alpha) = \frac{n_B}{M} \quad (3.16)$$

where n_A out of N building evacuations exceed ASET threshold, and n_B out of M response incidents exceed the ASET threshold.

For response time modeling, let Θ represent model parameters and $\mathcal{D} = \{t_i\}_{i=1}^N$ be observed response times. Bayes' theorem gives:

$$P(\Theta \mid \mathcal{D}) = \frac{P(\mathcal{D} \mid \Theta) \cdot P(\Theta)}{P(\mathcal{D})} \quad (3.17)$$

Response time comprises turnout time T_{to} plus travel time T_{tr} . Analysis of Istanbul fire department records shows that turnout time follows a lognormal distribution given by

$$\ln T_{\text{to}} \sim N(\mu_{\text{to}}, \sigma_{\text{to}}^2) \quad (3.18)$$

where μ_{to} and σ_{to}^2 are estimated from the Istanbul fire incident database.

The travel time component through Istanbul's street network also exhibits lognormal characteristics:

$$\ln T_{\text{tr}} \sim N(\mu_{\text{tr}}, \sigma_{\text{tr}}^2) \quad (3.19)$$

with parameters calibrated from the network analysis of fire station-to-building routes.

The probability density function for both turnout and travel time components is

$$f_T(t \mid \mu, \sigma) = \frac{1}{t\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln t - \mu)^2}{2\sigma^2}\right), \quad t > 0 \quad (3.20)$$

used to model the distribution of Istanbul fire brigade response times.

3.3.2. Analysis of Extreme Cases

To identify worst-case scenarios that guide contingency planning, extreme conditions combining peak traffic periods, tall buildings with high occupancy, and busy fire

stations can be analyzed. These scenarios represent the upper bounds of risk where both evacuation and response times are most likely to exceed safety thresholds.

In a worst-case residential fire scenario, a useful upper bound—independent of distributional form—is given by

$$R = \Pr(A \cap B) \leq \min\{\Pr(A), \Pr(B)\} = \min\{\Pr(\text{TET} > \alpha), \Pr(\text{FRT} > \alpha)\}. \quad (3.21)$$

These extreme scenarios provide critical insights for emergency planning and resource allocation, identifying conditions where standard response capabilities may be insufficient.

3.4. City-Scale Risk Analysis

3.4.1. Transportation Network Analysis

An origin–destination (OD) cost matrix is a tabular representation that records the minimum-cost routes between a set of origin points and a set of destination points, where "cost" can be expressed in distance, travel time, or monetized driving expenditure. By solving the least-cost path problem for every origin–destination pair, the OD matrix provides analytical outputs including optimal route geometry, cumulative distances, travel times, and associated costs.

The network-analysis sequence quantifies how quickly emergency resources can traverse the city's street network to reach high-rise incidents and potential evacuation destinations. The city's street network was represented as a directed graph in which each road segment e in Istanbul's street network has a travel-time impedance calculated as

$$\text{Impedance}_e = \frac{\text{Length}_e}{\text{Speed}_e} \quad (3.22)$$

where speeds are adjusted for Istanbul's traffic conditions using the congestion factor $F_p = 1.25$.

Using a network dataset, an OD-matrix analysis can be used to create a matrix showing travel times or distances along transportation network. The minimum-impedance path cost, τ , between every origin $i \in \Omega$ (fire stations) and destination $j \in \Delta$ (high-rise buildings) is computed as:

$$c_{ij}(\tau) = \min_{p \in P_{ij}} \sum_{e \in p} (t_{\text{dyn},e}(\tau) + t_{\text{turn},e}(\tau)) \quad (3.23)$$

where P_{ij} is the set of all feasible paths, e is an edge (road) segment, $t_{\text{dyn},e}$ represents the dynamic travel time along segment e at time τ , and $t_{\text{turn},e}$ denotes the additional delay incurred at intersections or required turning movements.

3.4.2. Thematic Risk Map

Thiessen polygons, also known as Voronoi diagrams, are a spatial partitioning method used to divide a region into distinct areas based on proximity to a set of predefined points. Each polygon contains exactly one generating point, and every location within the polygon is closer to its corresponding point than to any other point in the dataset. This method is widely used in geographic and urban analysis, particularly in cases where service areas or influence zones need to be determined.

By incorporating Voronoi polygon analysis into fire risk assessment, this study aims to provide a more accurate spatial visualization of fire risk. Each fire station in Istanbul defines a Voronoi polygon containing all locations closer to that station than any other. For a set of points $P = \{p_1, p_2, \dots, p_n\}$ in a plane, the Voronoi polygon $V(p_i)$ for point p_i is defined as:

$$V(p_i) = \{x \in \mathbb{R}^2 \mid d(x, p_i) \leq d(x, p_j) \text{ for all } j \neq i\} \quad (3.24)$$

where $d(x, p)$ represents the Euclidean distance between point x and p . In simple terms, each polygon contains exactly one generating point, and any location within a polygon is closer to its generating point than to any other as shown in Figure 3.16.

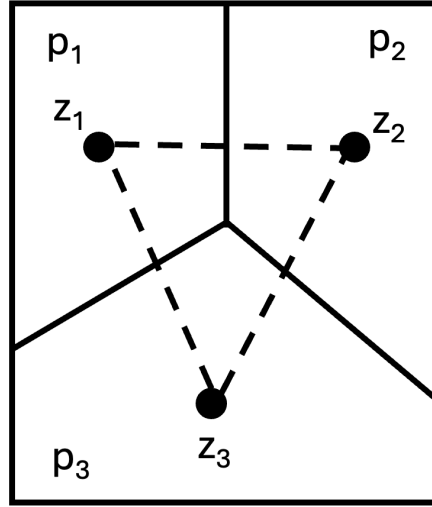


Figure 3.16. Voronoi (Theissen) polygons.

In the context of fire risk analysis, Thiessen polygons provide a useful approach for defining the coverage area of each fire station. By constructing Voronoi regions around fire station locations, it is possible to assess spatial variations in fire department intervention times. Areas farther from a fire station, as defined by their corresponding polygon boundaries, are likely to experience longer response times and, consequently, higher fire risk. This spatial representation allows for the identification of underserved regions where additional fire stations or resource reallocation may be necessary to improve emergency response efficiency.

For city-wide analysis, the study area is partitioned into Voronoi cells based on fire station locations. For each zone i , risk is defined as

$$R_i = P(A_i \cap B_i) = P(A_i) \times P(B_i) \quad (3.25)$$

This spatial distribution of risk values identifies high-risk areas requiring improved safety measures or emergency response coverage.

3.4.3. Fire Stations Site Suitability Analysis

Location–allocation modeling builds on these insights to determine the most effective ways to improve coverage. Here, potential fire stations are evaluated based on minimizing overall travel time, with algorithms iterating through different scenarios. Whether a single new station is added, or multiple mobile units are temporarily deployed, the selected model can identify the scenario that yields the greatest reduction in emergency response times. This ensures that future investments in infrastructure directly address the most critical gaps in service.

Service area analysis complements the routing and allocation steps by visualizing how far a fire engine can travel within a specific time frame under typical traffic conditions. Incorporating up-to-date speed limits, congestion data, or even variable time penalties helps in generating realistic coverage polygons around existing and proposed fire stations. Layering these polygons onto building footprints or hazard maps allows emergency managers to pinpoint the buildings most at risk, guiding decisions about station siting, hydrant installations, or stricter building regulations in areas that remain outside safe response intervals.

The city is divided into Voronoi cells based on fire station locations, and the optimization process is carried out for the most important and vulnerable cells. The importance index I_{voronoi} measures the importance of a Voronoi cell relative to other cells in the city. The importance of a cell is measured by comparing the total number of occupants at risk in high-rise residential buildings within that cell. The total number of occupants depends on the floor area and height of high-rise buildings. The relative importance of each Voronoi cell containing Istanbul’s high-rise residential buildings is

measured as

$$I_{\text{voronoi}} = \frac{\sum_{i=1}^n A_i H_i}{\sum_{i=1}^N A_i H_i} \quad (3.26)$$

where N represents the total inventory of high-rise residential buildings in the city.

The risk index for each Istanbul fire station zone, weighted by building vulnerability, is

$$R_{\text{voronoi}} = I_{\text{voronoi}} \frac{\sum_{i=1}^n V_i A_i H_i}{\sum_{i=1}^n A_i H_i} \quad (3.27)$$

where n is the number of buildings in the Voronoi cell, N is the total number of buildings in the city, V_i is the vulnerability index of each building at peak traffic period, A_i is the floor area, and H_i is the building height (number of floors) of each corresponding building.

The optimal location for a new fire station can be proposed by appropriately weighting the individual locations of vulnerable buildings. The weights ensure that the new station minimizes the risk index of a Voronoi cell and positions the station as close as possible to the maximum number of affected occupants.

The optimal x-coordinate for new fire stations in Istanbul's underserved areas is determined by

$$\bar{x} = \frac{\sum_{i=1}^n V_i A_i H_i x_i}{\sum_{i=1}^n V_i A_i H_i} \quad (3.28)$$

representing the vulnerability-weighted centroid longitude of high-rise buildings in each priority zone.

Similarly, the optimal y-coordinate is calculated as

$$\bar{y} = \frac{\sum_{i=1}^n V_i A_i H_i y_i}{\sum_{i=1}^n V_i A_i H_i} \quad (3.29)$$

providing the vulnerability-weighted centroid latitude for strategic station placement.

Using the new fire station location, response times for each building in the Voronoi cell are updated and the improvement achieved can be evaluated using:

$$\text{Improvement (\%)} = \frac{R_{\text{voronoi}(\text{old})} - R_{\text{voronoi}(\text{new})}}{R_{\text{voronoi}(\text{old})}} \times 100 \quad (3.30)$$

The composite suitability score for potential fire station sites in Istanbul is calculated as

$$S = w_1 C_1 + w_2 C_2 + w_3 C_3 + w_4 C_4 \quad (3.31)$$

where the four criteria and their corresponding weights are:

- C_1 : Voronoi cell risk index R_{voronoi} , with weight $w_1 = 0.4$
- C_2 : Improvement percentage from, with weight $w_2 = 0.3$
- C_3 : Voronoi cell importance index I_{voronoi} , with weight $w_3 = 0.2$
- C_4 : Aggregated building-level vulnerability V_i at peak traffic, normalized by cell floor area, with weight $w_4 = 0.1$

All criterion values are linearly reclassified to a common 0–1 scale prior to overlay so that S varies between 0 (lowest priority) and 1 (highest priority). The resulting suitability surface balances the magnitude of expected loss, the capacity for response-time improvement, the scale of occupant exposure, and the severity of vulnerability under peak conditions. Voronoi cells with the highest composite scores represent priority areas for new fire station placement.

4. DATASET AND STUDY AREA

This chapter details the analytics of the geospatial and tabular datasets employed for city-scale fire risk monitoring and describes the geographic, infrastructural, and demographic characteristics of Istanbul Province in Türkiye. Section 4.1 identifies the sources and attributes of each of the dataset used for the study. Section 4.2 outlines data collection strategies and quality-control procedures, detailing the acquisition, preprocessing, and integration workflow that produced an analysis-ready master geodatabase. Section 4.3 situates these cleaned layers within Istanbul’s context, focusing on the distribution of high-rise buildings, the configuration of emergency-service assets, the characteristics of potential building occupants, the structure of the road network, and the spatiotemporal pattern of historical fire incidents.

4.1. Data Sources and Attributes

A suite of spatial and tabular multiscale datasets was assembled from official and reputable open-access repositories for this study. These are listed in Table 4.1. High-rise residential building location data define *demand points* for both the evacuation simulation (Chapter 5) and the network coverage metrics (Chapter 6). Fire station locations represent *supply nodes* in location–allocation models, driving origin for response-time. Historical fire incident logs provide empirical travel-time distributions and hot-spot baselines to calibrate peak-hour speed factors. The location is stored as street addresses in the data tables. Road network dataset forms the topological backbone for service-area, OD-matrix, and route-optimization analysis, providing impedance (travel-time and distance) surface for all network metrics.

Table 4.1. Sources of key datasets.

Dataset	Source	Key Attributes	Format
Administrative Boundaries	Self-digitized at scale of 1:100,000 or more	DistrictID, DistrictName, ShapeLength, ShapeArea, Population, Esri Topographic basemap	gdb
High-Rise Residential Buildings	Istanbul Municipality (İBB)	BuildingID, Coordinates, NumberOfFloors, ShapeLength, ShapeArea, DistrictUAVT, NeighborhoodUAVT	xlsx
Fire Stations	Istanbul Fire Department (İstanbul İtfaiyesi)	StationName, District, Location, EngineCount, StaffCount, StationStatus	xlsx
Historical Fire Incidents	Istanbul Fire Department (İstanbul İtfaiyesi)	IncidentID, Date, Time, Location, NotificationTime, DutyAssignTime, TurnoutTime, ArrivalTime, ExtinguishTime, DepartureTime, ArrivalBackTime	xlsx
Fire Hydrants	Istanbul Fire Department (İstanbul İtfaiyesi)	HydrantID, Coordinates	xlsx
Road Network	OpenStreetMap (via Geofabrik Export)	OSMID, RoadType, SpeedLimit, OneWay, Length	shp

Fire hydrant data provide the spatial positions and rated flow capacities of municipal water points, enabling us to assess on-scene water availability and optimize routing orders to the nearest high-capacity hydrant during fire scenarios. Administrative boundaries enable demographic normalization (per-capita risk), policy-relevant summary statistics, and cartographic framing. This feature class was vectorized in ArcGIS Pro at a scale not less than 1:100,000.

A Microsoft Excel workbook (.xlsx) stores one or more sheets of tabular data (rows & columns), ideal for attribute tables of vector geospatial data types. In comma-separated values (csv) text files, each line is a record, fields separated by commas, easily read by almost any GIS, database, or scripting language as well as for simple attribute exports.

An ESRI Shapefile (shp), which comprises several files (.shp geometry, .shx index, .dbf attributes, etc.), stores both vector features (points, lines, polygons) and their attribute table. ESRI File Geodatabase (gdb), on the other hand, is a newer, more advanced data storage comprising a folder-based container that can hold multiple feature classes, tables, raster datasets, and relationships in a single workspace. This ESRI proprietary option offers richer and optional topology rules as well as more indexing than shapefiles to bundle and manage multiple layers, enforce topology, or run advanced network and spatial analyses.

4.2. Data Collection and Preprocessing

This section documents the end-to-end workflow that converted the raw layers listed in Table 4.1 into a single, analysis-ready geodatabase. The process was implemented in ArcGIS Pro 3.4. Preprocessing steps included the following.

- (i) Topology validation: checking and repairing polygon overlaps and gaps in building footprints and administrative boundaries.

- (ii) Attribute harmonization: standardizing field names (e.g., StationID vs. ID), converting date/time formats, and reconciling usage type categories against a controlled vocabulary.
- (iii) Coordinate systems and projection: the mathematical framework that ties map coordinates to real-world locations on the Earth's surface. There are two principal types of coordinate systems:
 - (a) Geographic Coordinate System, which uses angular units (latitude, longitude) on a defined ellipsoid; and
 - (b) Projected Coordinate System, which "flattens" the curved surface onto a plane via a map projection, enabling accurate distance and area measurements.
- (iv) Road network simplification: removing OSM features irrelevant to fire-engine routing (e.g., pedestrian-only paths, service roads), merging segmented road centerlines into continuous segments for major arterials, and assigning travel time impedances based on speed limits and time-of-day factors.
- (v) Geocoding and spatial join: Converting incident coordinate logs into point features and joining them with nearest road segments for network analysis.
- (vi) Outlier detection: Identifying and flagging records with implausible response times (< 30 s or > 60 min), missing geometry, or duplicate incident entries.

A master geodatabase was then constructed in ArcGIS Pro, containing cleaned feature classes and related tables, ready for network dataset creation and suitability modeling.

4.2.1. Topological Validation

The ESRI File Geodatabase supports the definition and enforcement of topology rules, enabling datasets to maintain spatial integrity and detect common errors such as overlaps, gaps, and dangles across large feature classes. Unlike shapefiles, which are simple flat files, a geodatabase allows users to explicitly define relationships among features (e.g., "polygons must not overlap," "lines must be connected at endpoints"),

automate error detection, and perform scalable corrections (Esri, 2024). This facilitates higher data quality and ensures that analyses dependent on topological relationships, such as network routing and areal aggregations, are based on geometrically valid inputs. Since the administrative boundaries were self-digitized, vector layers were subjected to the *Validate Topology* workflow (Esri, 2024). All three vector data types were topologically validated.

- Polygons — slivers and overlaps were fixed with *Eliminate*; no features required manual editing.
- Lines — dangling road segments not connected to any junction class were trimmed; legitimate cul-de-sacs (dead-end streets) were preserved by attribute flagging.
- Points — duplicate fire station, incident records centroids, and high-rise residential buildings within 5 m were merged after field comparison confirmed they were alias records for the same date and time in the case of incident records.

4.2.2. Attribute Harmonization

Fire station and incident records often had inconsistent naming conventions or incomplete fields. These were standardized by assigning proper station IDs and ensuring all attributes matched standardized data dictionaries. Field names and types were standardized across tables. Date/time fields, often saved as text format, were converted to ISO 8601 format. Numeric fields (e.g., floor count, population) cast to integer or float types, enforcing non-null constraints where applicable.

4.2.3. Coordinate Systems and Projection

Accurate spatial analysis at city scale demands a consistent, conformal map projection that minimizes distortion throughout the study extent. For this purpose, all vector and raster layers were re-projected to the WGS 84 / UTM Zone 35 N coordinate reference system (EPSG:32635). The Universal Transverse Mercator (UTM) projection is particularly well suited to mid-latitude regions such as Istanbul, as it preserves local

angles and shapes (conformality) and limits linear distortion to less than 1 part in 10,000 within each 6° longitudinal zone (Clynch, 2003).

To quantify the accuracy of the datum transformation, control-point coordinates were compared before and after reprojection using the Spatial Reference inspector. Maximum observed shifts never exceeded 0.7 m, an order of magnitude below the 10 m snapping tolerance subsequently applied when aligning incident and network features. Such sub-meter residual errors are negligible in the context of emergency-response routing, where turn-by-turn accuracy is bounded by roadway widths and positional uncertainty in GPS logs.

Finally, all projection parameters—the geographic datum (WGS 84), projection method (Transverse Mercator), central meridian (33° E), scale factor (0.9996), false easting (500,000 m), and false northing (0 m)—were cross-checked against the authoritative EPSG registry within ArcGIS Pro’s *Spatial Reference* dialog to guarantee compliance with international geodetic conventions.

4.2.4. Network Dataset

Although the OpenStreetMap (OSM) extract provides a geometrically accurate poly-line representation of Istanbul’s streets, effective routing and coverage analysis require a network dataset—a topologically connected data structure that stores cost attributes, turn restrictions, and evaluators understood by the ArcGIS Pro Network Analyst extension. The conversion from a raw line layer to an analysis-ready model was therefore carried out in six sequential stages, each underpinned by standard GIS workflows as follows.

- (i) Thematic filtering and topological simplification. The initial shapefile contains edges with segments whose attribute `highway` $\in \{\textit{footway}, \textit{cycleway}, \textit{steps}, \textit{service}\}$ or whose `access` = private were excluded, consistent with NFPA 1901 guidance that heavy apparatus should avoid non-carriageway facilities. Residual artefacts

arising from OSM’s volunteer digitization—principally oversampling of divided arterials—were removed by dissolving contiguous segments that shared identical values of name, maxspeed, and one-way.

- (ii) Spatial reference unification. All geometries were re-projected to WGS 84 / UTM Zone 35 N (EPSG 32635) using a high-order Helmert transformation. Datum shifts never exceeded 0.7 m—well below the 10 m snapping tolerance adopted during edge alignment—thereby ensuring metric integrity in subsequent impedance calculations.
- (iii) Cost-attribute construction. Two principal impedance fields were created. First, TT_{off} (off-peak travel time) was computed as

$$TT_{\text{off}} = \frac{L_i}{V_i} \quad (4.1)$$

where L_i denotes segment length (km) and V_i the posted speed limit (km h^{-1}). Second, TT_{peak} was derived by multiplying TT_{off} by a congestion factor $F_p = 1.25$, calibrated from 70,000 probe-speed observations for the March–May 2024 period. This dual-cost schema allows the present work to report both best-case and worst-case accessibility scenarios in Chapter 6.

- (iv) Network-dataset compilation and travel-mode definition. Using the *Create Network Dataset* wizard, edges, turns, and junctions were compiled into a dataset named IST.Routing.ND. Connectivity policies were differentiated by functional class (“Endpoint” connectivity for local streets; “Any Vertex” for divided arterials) to prevent artificial breaks in dual-carriageway corridors. A custom travel mode entitled FireEngine was then created with the following specifications: impedance = TT_{peak} ; u-turns permitted; OneWay honoured.

The resulting network dataset supports three Network Analyst layer types employed later in this study (Section 6.2). By adhering to a transparent, literature-based conversion protocol, the study ensures that all emergency-response metrics reflect both the geometric as well as the operational constraints of Istanbul’s urban transport system.

4.2.5. Geocoding

Historical incident addresses —recorded as free-text strings in the İBB incident log— were geocoded to geographic coordinates using the ArcGIS World Geocoding Service to obtain precise latitude–longitude pairs. Using ArcGIS Pro’s Geocode Addresses tool, each record was submitted to the World Geocoding Service, returning candidate locations with match scores. The resulting point feature class thus contains rigorously validated, meter-level coordinate positions for all incident logs. This geocoded layer was then used exclusively for address mapping and point-based analyses—separate from but compatible with the later network-based routing and spatial-overlay workflows.

4.3. Istanbul and its Urban Context

This section synthesizes the processed datasets to characterize Istanbul’s built environment, demographic composition, transportation infrastructure, and historical fire activity. By situating the core spatial layers within their real-world patterns, we establish the empirical foundation for the evacuation simulations (Chapter 5) and network-based risk assessments (Chapter 6).

4.3.1. High-Rise Residential Building Distribution

A high-rise building is defined as a building with 15 floors above the floor fire rescue can operate. The inventory comprised 1,167 high-rise residential buildings—each defined as having at least 15 storeys—across the City of Istanbul. The distribution of storey counts was found to range from 15 to 62 floors, with a mean of 19 floors and a standard deviation of 6.2 floors.

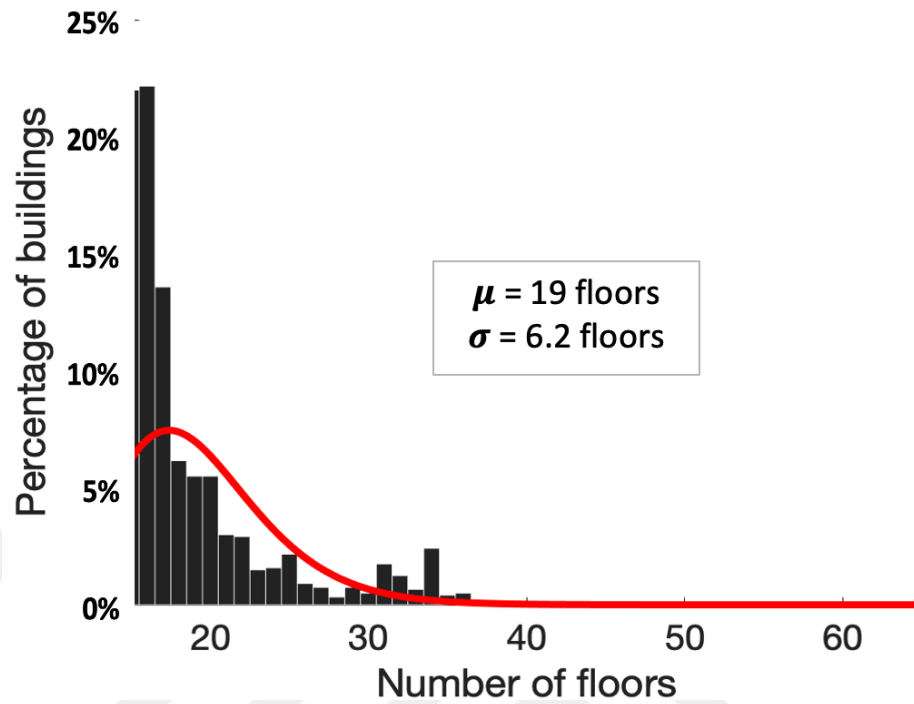


Figure 4.1. Distribution of number of floors of high-rise residential buildings in Istanbul.

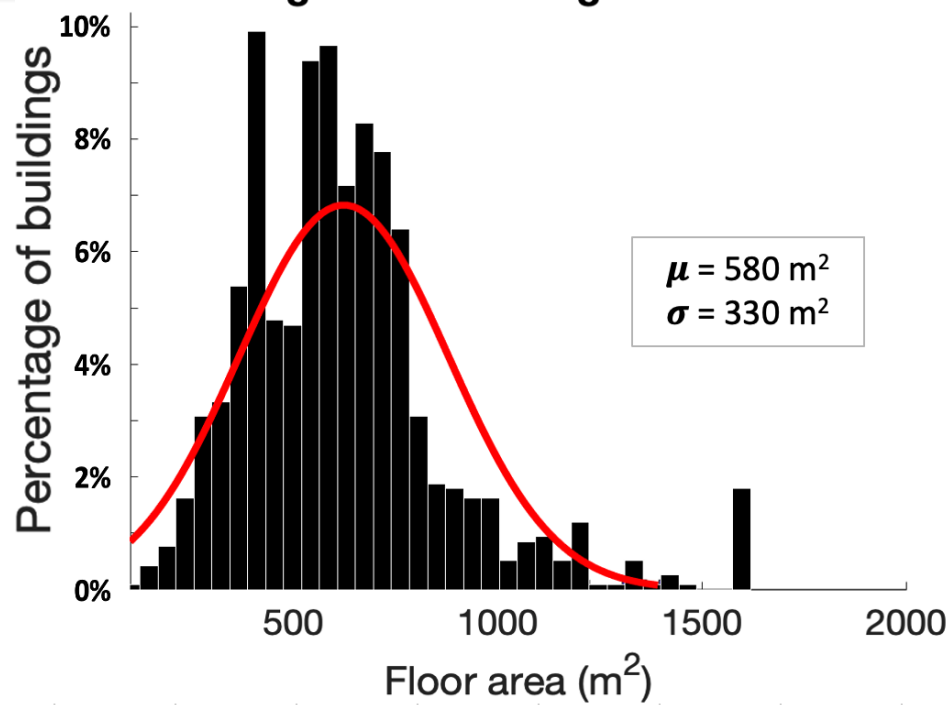


Figure 4.2. Distribution of floor area of high-rise residential buildings in Istanbul.

4.3.2. Fire Stations Service Coverage

Istanbul's municipal fire service is organized around 103 career and auxiliary volunteer fire stations (Istanbul Metropolitan Municipality, 2020). Stations are stratified into three operational tiers—primary metropolitan, district, and satellite—according to catchment size, call volume, and equipment complement. Based on the number of pumpers, aerial ladder, and a hazardous-materials unit, as well as district command for reinforcement during multi-alarm events.



Figure 4.3. Fire engines in an Istanbul fire station.

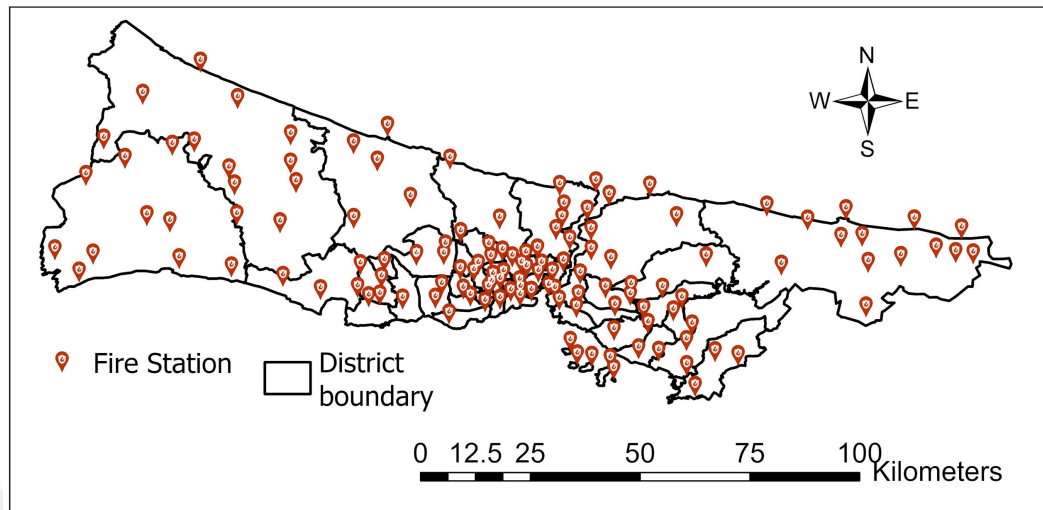


Figure 4.4. Fire station locations in Istanbul Province.

Voronoi polygon analysis facilitates comparisons between administrative district-based risk assessment and station-based coverage models. As Figure 4.6 shows, while district boundaries often reflect political or administrative divisions, Voronoi-based regions offer a more functional approach by accounting for actual proximity to fire stations. This makes it an effective tool for evaluating fire service accessibility and optimizing station placement to reduce response delays.

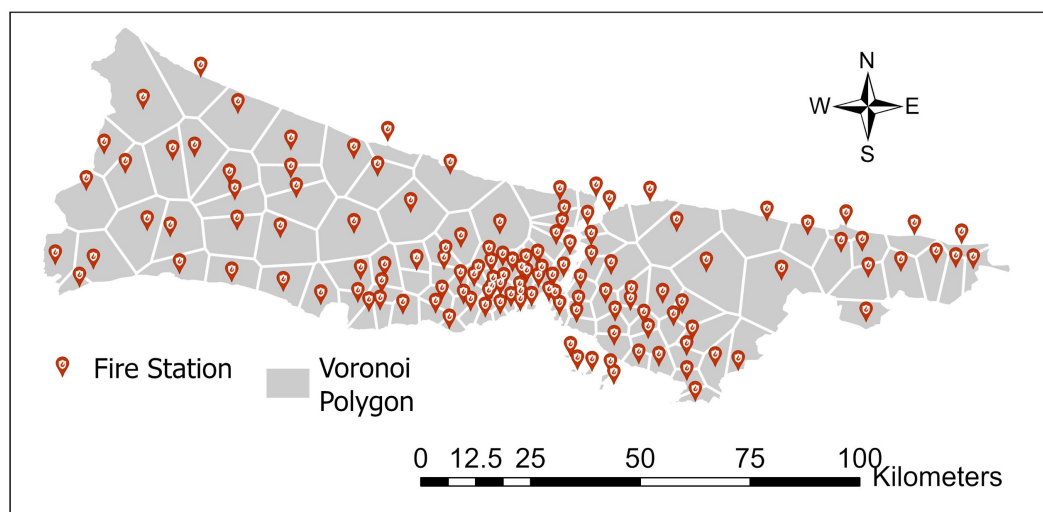


Figure 4.5. Voronoi polygons around Istanbul's fire stations.

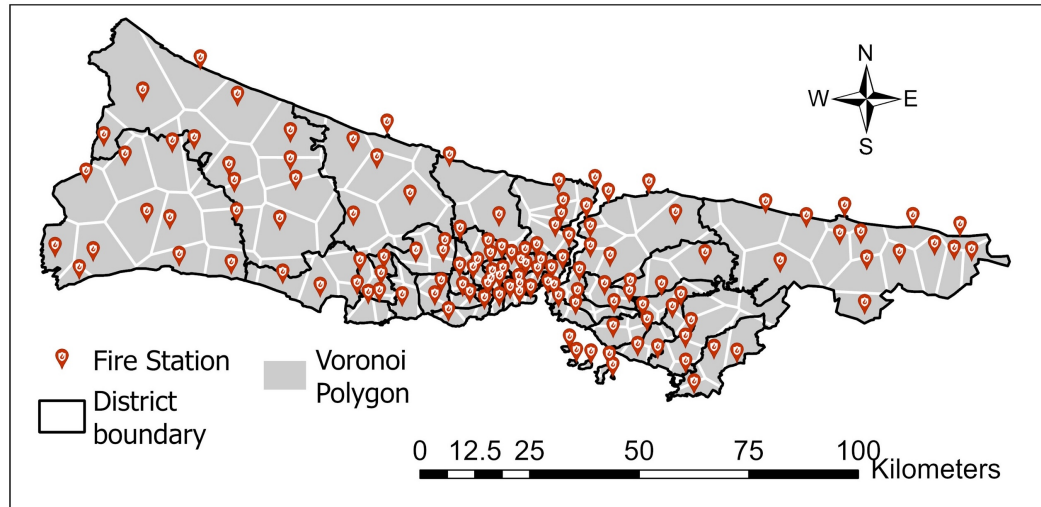


Figure 4.6. Comparison of Istanbul's Voronoi polygon- and district-based fire stations.

4.3.3. Historical Fire Incidents

Fire Station location data was acquired from Istanbul's Fire Department records. The dataset includes station addresses, operational capacities, and resource details (vehicles, staff). Fire incidents. The selected timeframe covered for the year 2024 to incorporate up-to-date built environment changes, newly built roads, and updated emergency response infrastructure. This ensured that the analysis closely reflected current urban realities and could guide more immediate decision-making.

Station-level information was obtained directly from the Istanbul Fire Department's under a formal data-sharing agreement. The dataset comprises:

- Spatial attributes: Precise street addresses and coordinates for each of the 46 career stations and nine volunteer outposts.
- Operational capacities: Counts of frontline pumpers, aerial ladder trucks, specialized rescue units, and ancillary support vehicles assigned to each station.
- Personnel resources: Total rostered staffing levels per shift, including breakdowns by rank and qualification (e.g. driver, engine operator, rescue technician).

All station records reflect the January–December 2024 inventory, ensuring that subsequent spatial and network analyses incorporate newly commissioned facilities, apparatus redeployments, and any station relocations effected during that calendar year. By aligning the station dataset’s temporal horizon with the 2024 roadway and building-footprint revisions, the geodatabase preserves internal consistency and closely mirrors the city’s most current emergency-response infrastructure.

Figure 4.7 illustrates the spatial extent of Istanbul Province, delineated into its constituent districts, overlaid by the complete road centerline network, representing highways, arterials, collectors and local streets. This comprehensive network layer forms the basis for constructing a network dataset used in subsequent shortest-path and travel-time analyses of fire brigade response across high-rise residential areas.

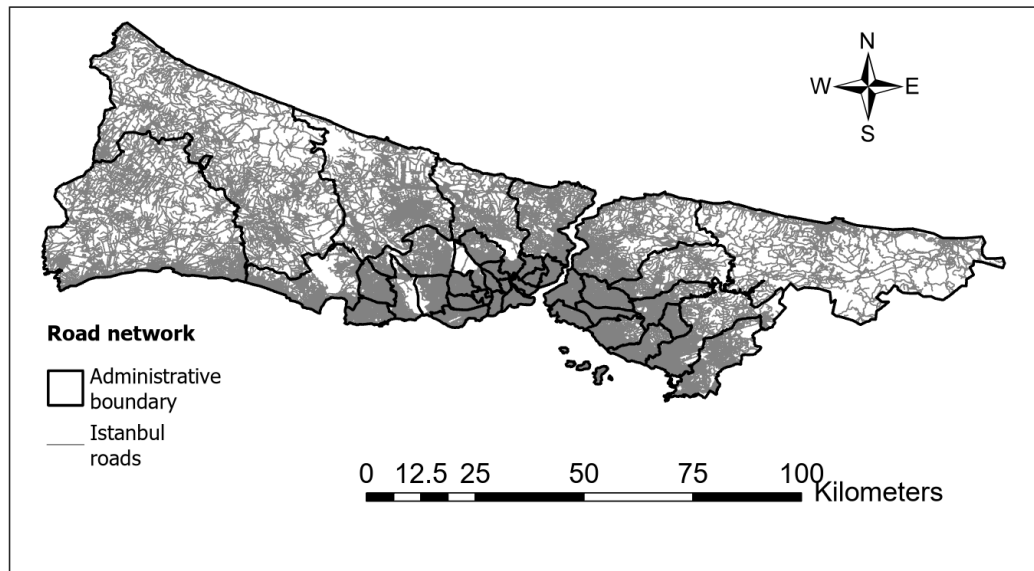


Figure 4.7. Transportation network of Istanbul Municipality.

5. OCCUPANT EVACUATION ANALYSIS

The analysis of building evacuation performance is a critical component of fire disaster preparedness. This chapter presents the results of the parametric evacuation simulations outlined in Chapter 3, applied to a representative high-rise residential building in Istanbul. The evacuation simulation was run under a range of scenarios (varying floor counts and occupant loads). The resulting evacuation times and flow rates were analyzed to identify bottlenecks and high-risk conditions. The results are expressed in terms of time-history profiles and summary metrics (total time to evacuate) for each scenario.

The following sections detail the fire scenario simulation (Section 5.1), parametric evacuation simulation results (Section 5.2), the application of queuing thresholds (Section 5.3), and the derivation of evacuation flow rates (Section 5.4).

5.1. Fire Scenario Simulation

To assess the effect of smoke propagation on occupant evacuation speed in a high-rise context, a living-room fire scenario on the 6th floor was simulated using Fire Dynamics Simulator (FDS). The fire was specified in PyroSim with a peak heat release rate (RHR) of 12.94 MW, yielding a characteristic fire diameter $D^* = 2.67$ m. Mesh resolution was set at 0.25 m to satisfy the criterion of at least ten cells per D^* (McGrattan et al., 2013). A Prandtl number of 0.7 and a Courant–Friedrichs–Lewy (CFL) number between 0.8 and 1.0 ensured numerical stability, while radiation-driven fire spread was neglected to focus exclusively on smoke transport. Figure 5.1 shows the mesh sensitivity analysis.

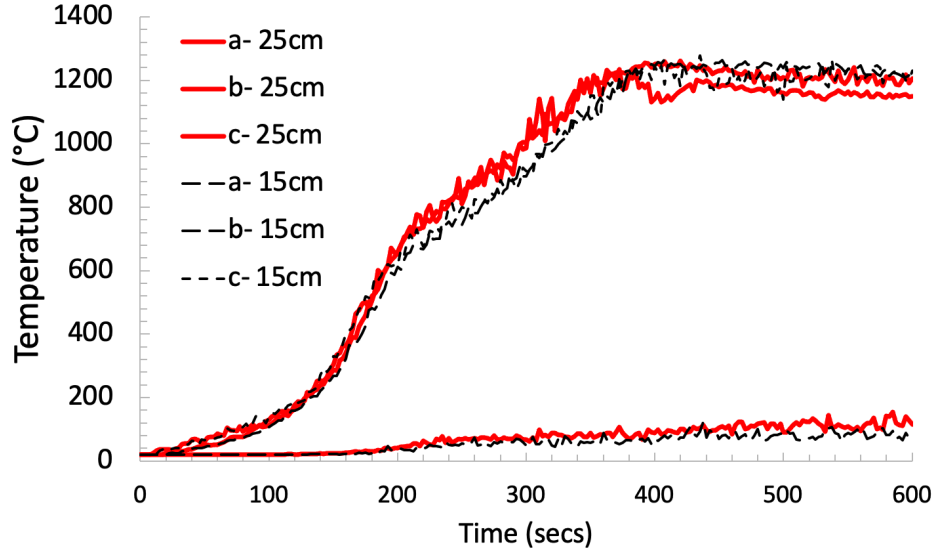
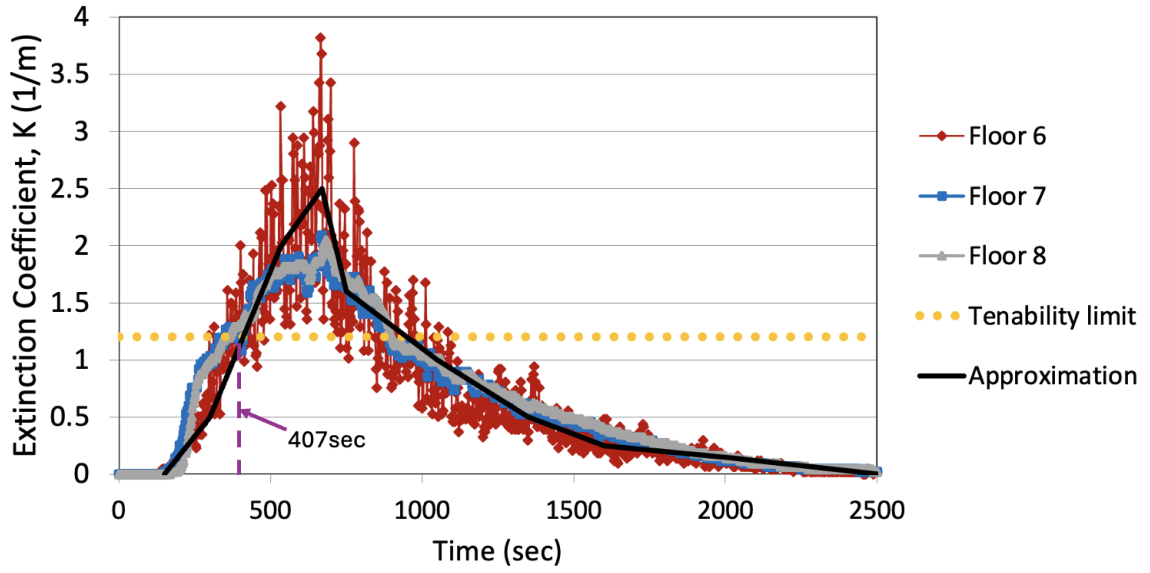


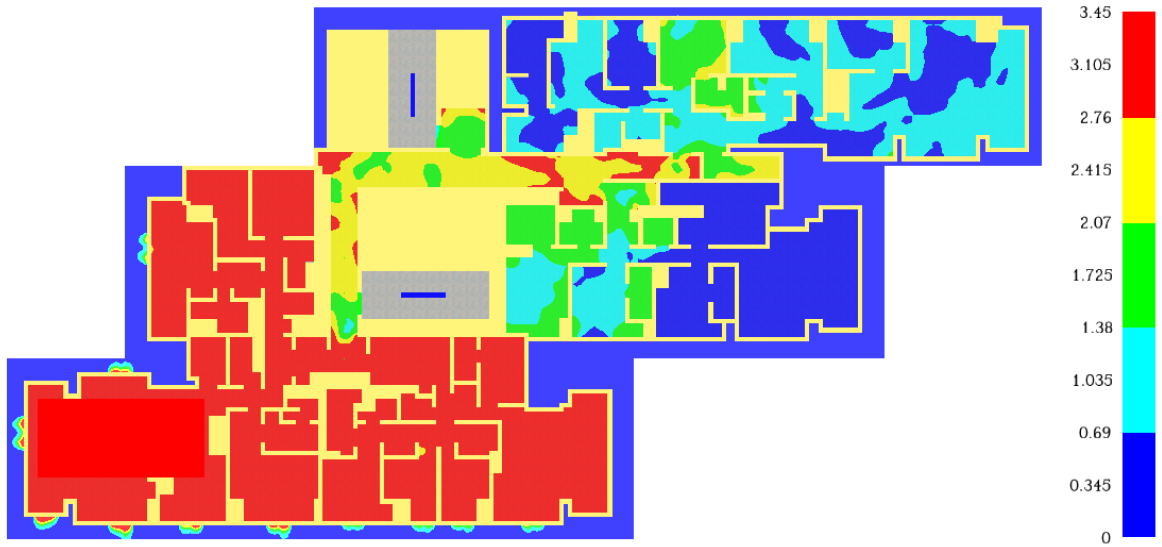
Figure 5.1. Mesh sensitivity analysis: comparison of temperature-time curves for 25 cm and 15 cm cell sizes.

The fire scenario is situated in the living room on the 6th floor and create a high extinction coefficient in the stairwells, which directly affects the occupant travel speed further exposing occupants to higher risk. Figure 5.2a shows the extinction coefficient vs. time history, which peaks to $0.5 \frac{1}{m}$ at around 20th minute in both stairs on the fire affected floors (i.e., Floors 6 through 8). Figure 5.2b shows the extinction coefficient distribution on Floor 6. The smoke concentration resulting from this fire scenario is deliberately chosen as mild enough that no occupant is intoxicated and trapped in the building but realistic enough to evaluate effect on occupants' speed. In the context of domestic fires, a tenability threshold limit of $1.2 \frac{1}{m}$ for the extinction coefficient is usually suggested (Purser and Bensilum, 2001).

As a result, the ASET threshold adopted for the probabilistic analyses in the next chapter is defined as the time required for the stairwell extinction coefficient to reach this tenability limit of 1.2 m^{-1} . As depicted in Figure 5.2a, this criterion is first exceeded at 407s following fire ignition. Consequently, an ASET value of 407s (6.8 mins) will be used as the critical temporal boundary for all subsequent probability calculations.



(a)



(b)

Figure 5.2. Estimated extinction coefficient (a) on the stairs of the fire floor, (b) map at $t = 20^{th}$ minute ($K = 1.21m$ is the tenability threshold).

5.2. Parametric Evacuation Simulation

Building upon the spatial configuration outlined in the previous dataset chapter, occupants are distributed across four principal apartments (A–D) and their movement toward exits is modeled based on corridor connectivity, elevator access, and stairwell

availability. The representative building has two stairways. The randomness in the number of people evacuated is reflected in the fluctuations in the flow of people from exits and in the amount of time it takes to evacuate an occupied building. Occupants are initially distributed randomly across all apartments, consistent with plausible usage densities.

In the base case with no smoke effect on occupant evacuation, the TET equation for Istanbul's high-rise residential buildings as a function of the number of floors (β) and the number of occupants per floor (γ) is given by

$$\text{TET} = \begin{cases} 24.6\beta + 18.7\gamma - 422 & \text{for } \gamma \geq \gamma_{\text{threshold}} \\ 24.6\beta + 148 & \text{for } \gamma < \gamma_{\text{threshold}} \end{cases} \quad (5.1)$$

derived from evacuation simulations of typical Istanbul residential building configurations. Figure 5.3 shows a simple linear fit for TET increase with floor occupancy.

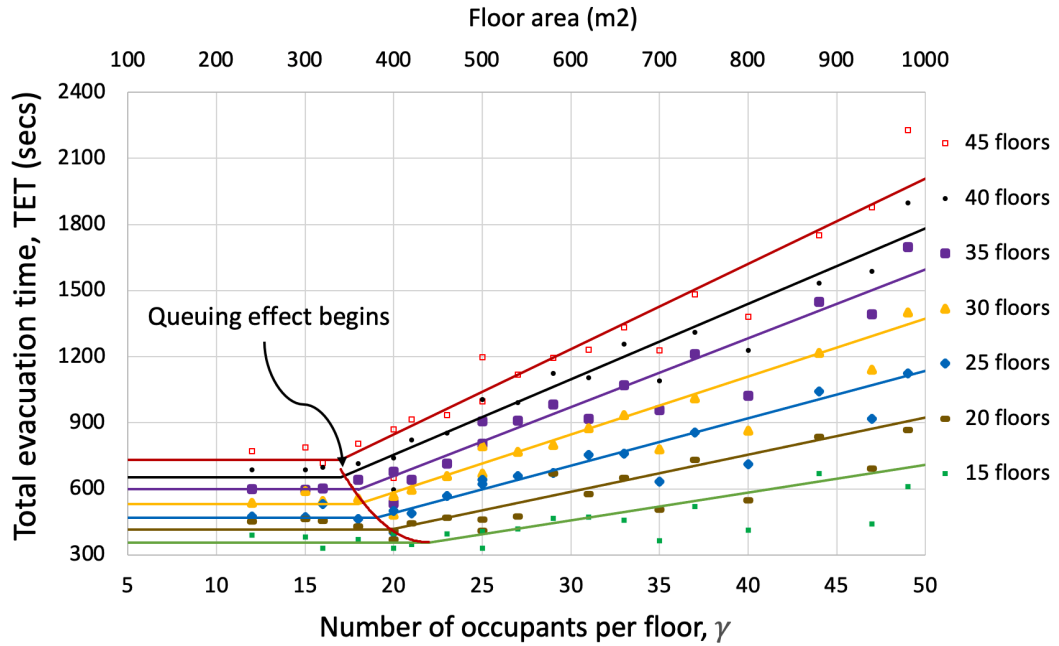


Figure 5.3. Comparison of calculated and simulated total evacuation time (TET) of 315 representative high-rise residential buildings.

The effect of irritant smoke on the total evacuation time is extended to cover a range of building heights and occupant numbers per floor. The parametric study shown in Figure 5.4 shows the increase in TET with the effect of smoke extinction coefficient. When compared to Figure 5.3, it is observed TET is significantly affected only for high-rise residential buildings above 30 floors. The total evacuation time increases by up to 60% with the given fire scenario on the 6th floor. For 20-floor and 25-floor buildings, there is slight increase in TET only for large floor areas, which corresponds to large number of occupants per floor.

The formula for TET considering the effect of smoke extinction coefficient on evacuation in Istanbul's high-rise buildings is expressed as

$$(\text{TET})_{\text{with fire effect}} = \begin{cases} 40.2\beta + 28.6\gamma - 983 & \text{for } \gamma \geq \gamma_{\text{threshold}} \\ 40.2\beta + 28.6\gamma_{\text{threshold}} - 983 & \text{for } \gamma < \gamma_{\text{threshold}} \end{cases} \quad (5.2)$$

accounting for reduced visibility and movement speed during evacuation.

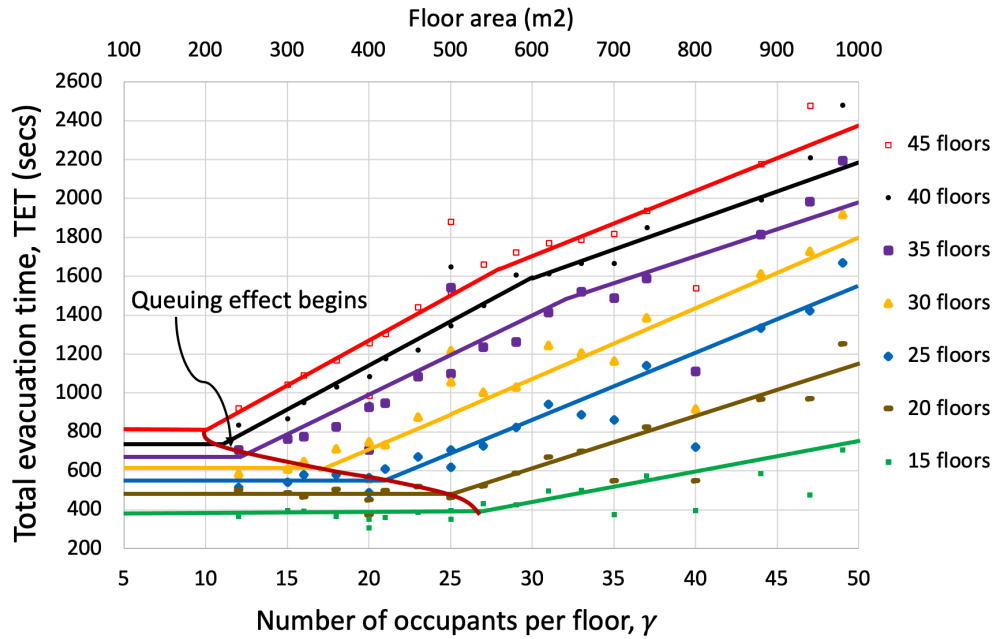


Figure 5.4. Simulated total evacuation time (TET) with the effect of smoke on occupant movement.

5.3. Queuing Threshold Occupancy

The previous section has shown that queuing in high-rise evacuation starts only after a threshold occupancy level. Thus, the speed of evacuation cannot be solved by adding more exits or egress pathways in these buildings. The other aspect of disaster response is the rescue services. for response service need to be based on calculated risk, which can change with time. Queuing is formed either when the demand exceeds capacity for a period of time or when the arrival time headway is less than the service time.

Figure 5.5 shows the three-dimensional relationship among total evacuation time, number of floors (β), and number of occupants per floor (γ). The surface remains relatively smooth and gently sloping at lower γ values, indicating that evacuation time increases approximately linearly with building height when stair capacity is not fully utilized. However, as γ increases beyond approximately 20–25 occupants per floor, the surface steepens markedly, reflecting the onset of queuing delays in the stairwells.

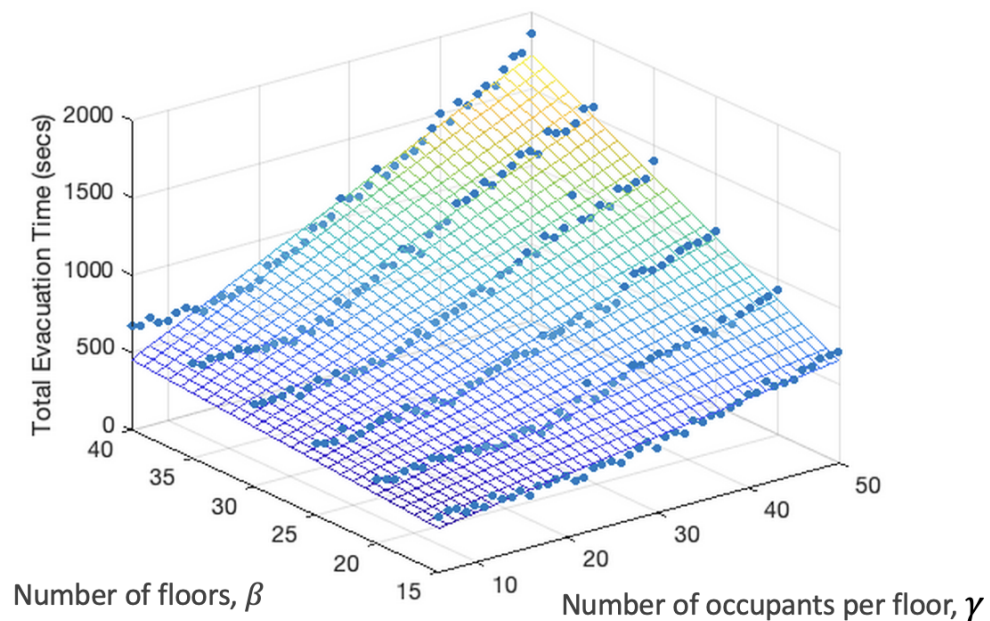


Figure 5.5. Queuing threshold for number of occupants per floor without pre-threshold constant regime.

Figure 5.6 presents a more focused view of this threshold behavior by plotting evacuation time against occupant density for fixed building heights. These results demonstrate that simply adding more exit routes or egress pathways may not alleviate delays once the critical density threshold is reached; instead, control of occupant loads or implementation of phased evacuation strategies is required to prevent stairwell congestion.

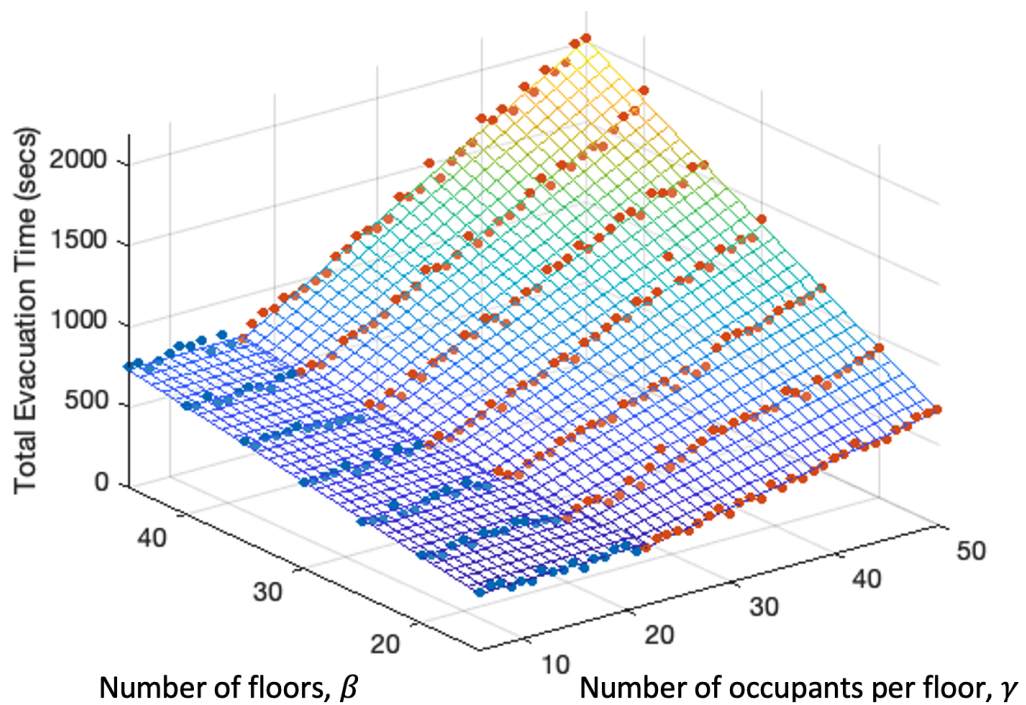


Figure 5.6. Queuing threshold for number of occupants per floor with pre-threshold constant regime.

Figure 5.7 uses a contour map to show how total evacuation time grows as both the number of stories and the number of occupants per floor increase. Along the lower-left corner—where buildings are shorter and less crowded—contours are spaced far apart, indicating that modest changes in height or occupancy have only a small impact on evacuation duration. Moving toward the upper-right—taller, denser towers—the contours pack closely together, reflecting the rapidly compounding delay as more people must travel farther to reach exits. In essence, this visualization highlights the dual influence of building height and floor-level occupancy on egress efficiency, revealing

critical “regions” where response plans and design interventions must be most attentive to avoid exceeding acceptable evacuation thresholds.

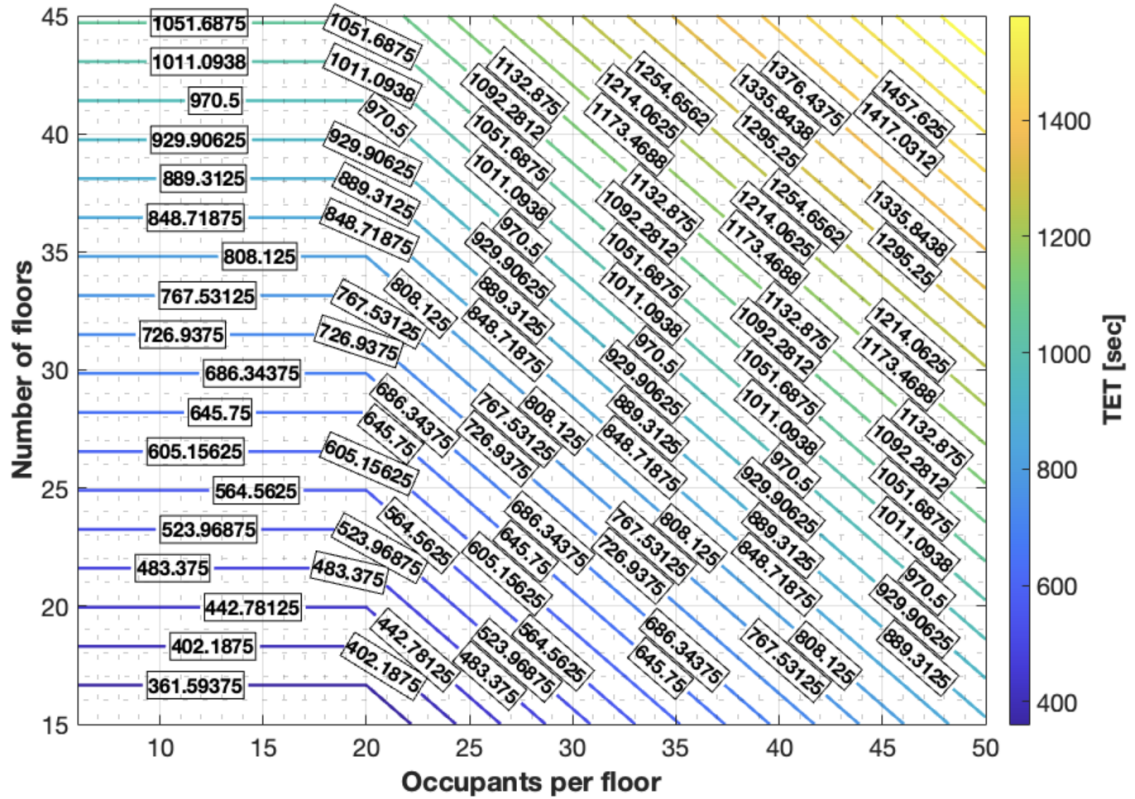


Figure 5.7. Total Evacuation Time contour plot.

The probability distribution of total evacuation time (TET) for the high-rise residential building in Istanbul is presented in Figure 5.8. The evacuation times exhibit a sample mean of 8.6 min and a standard deviation of 3.3 min. This mean value is about 69% higher than the ASET threshold calculated earlier. Consequently, without additional smoke-control or egress-enhancement measures, occupants are likely to encounter hazardous conditions during evacuation, highlighting the need for improved fire-safety interventions.

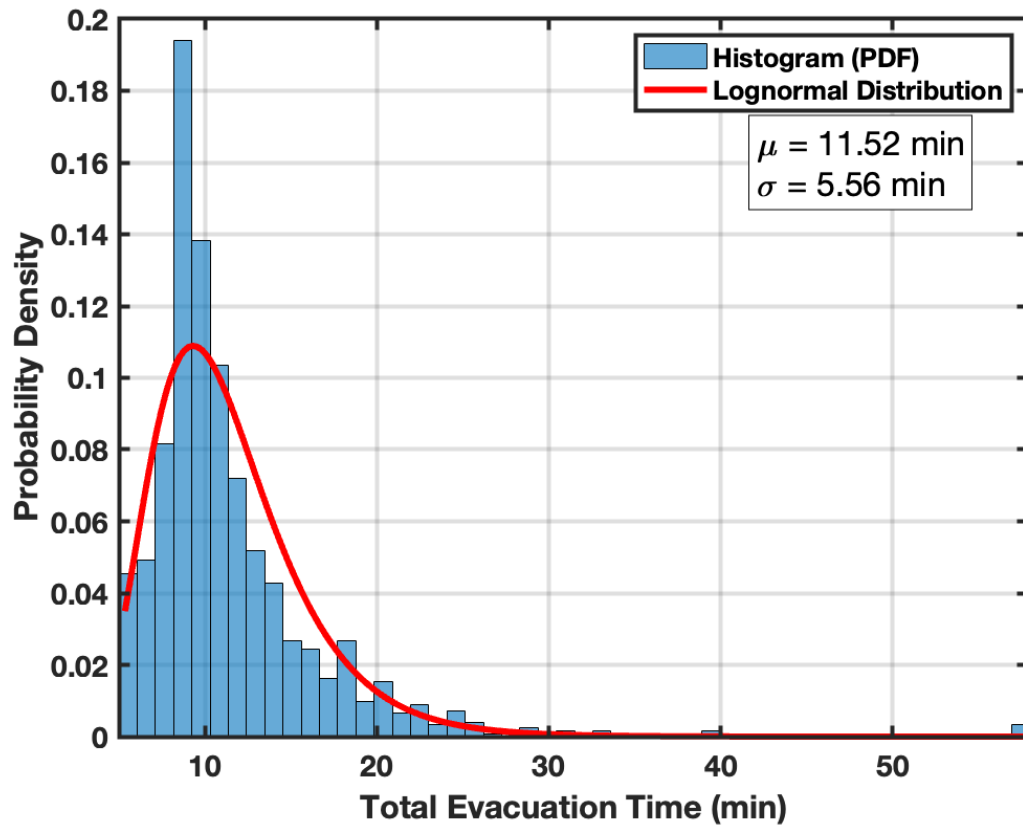


Figure 5.8. PDF of TET.

5.4. Evacuation Flow Rate

The evacuation-flow-rate analysis quantifies the capacity of the stairwell system by examining the rate at which occupants exit the building over time, thereby linking individual movement dynamics to aggregate evacuation performance. Figure 5.9 give a sample of the rate at which occupants exit the building taking into account the floor origin of each occupant.

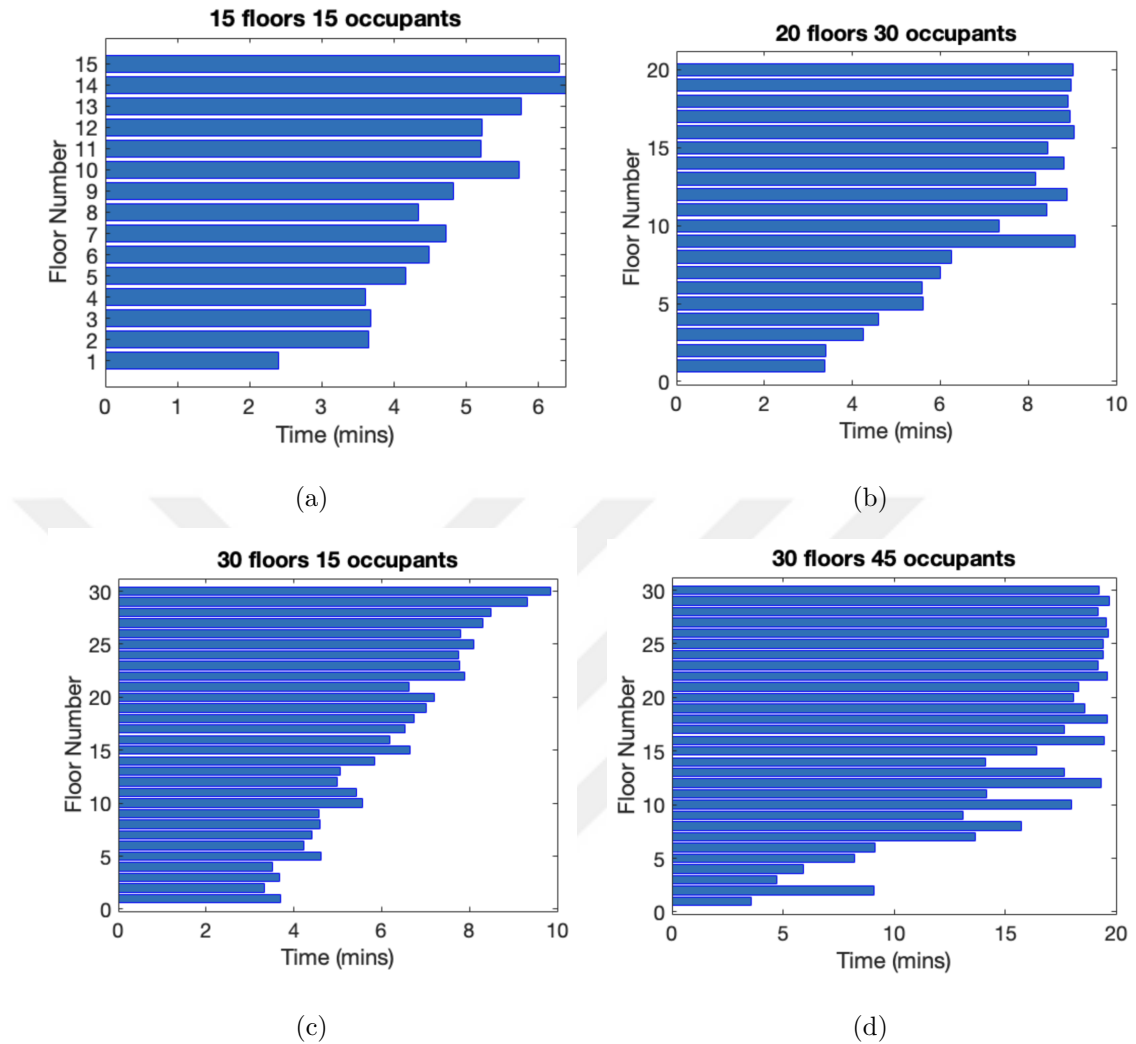


Figure 5.9. Evacuation completion for occupants from each floor: (a) 15 floors, (b) 25 floors, (c) 35 floors, and (d) 45 floors.

Evacuation of a high-rise building in fire proceeds from occupants on the floors below and progresses to floors above. An exit time graph can be plotted to show floor by floor evacuation of a building, such as those shown in Figure 5.10 and Figure 5.11 for the smallest area with 12 occupants per floor for the largest area with 47 occupants per floor. The time difference between first and last occupant to exit the building completely, i.e., complete evacuation for each floor, called the exit time range, with lower and upper curves linking the first occupants on all floors to exit the building and the last occupants to exit all floors.

With a small floor area, the upper and lower curves increase linearly with floor number, indicating fixed time for movement on the floor and vertical evacuation time proportional to floor height. However, with a large number of occupants per floor, occupants on the upper floors would have to spend a considerable amount of time queuing to exit the building, with the exit time on many floors being very similar. The upper curves increase nonlinearly with floor number.

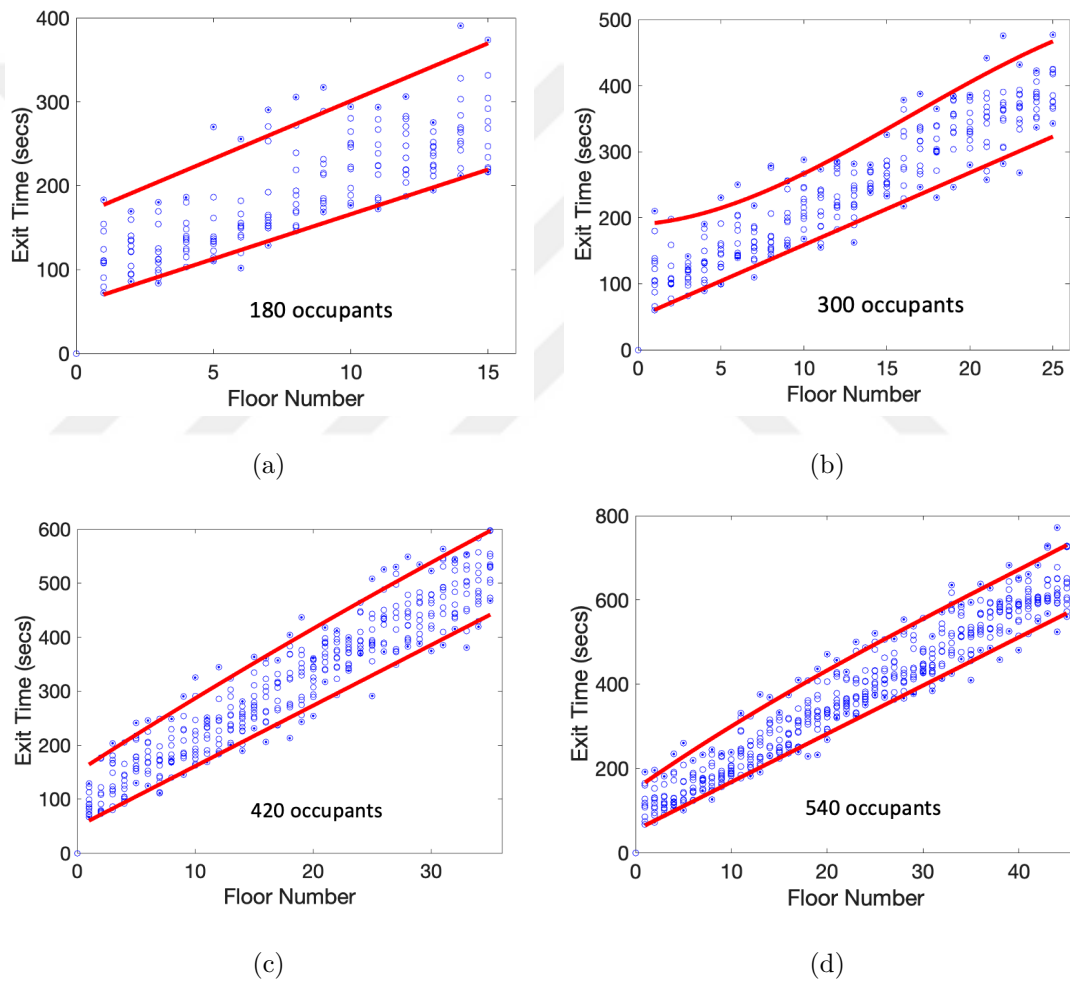


Figure 5.10. Evacuation of occupants from a number representative residential high-rise building for: (a) 15 floors with 12 occupants per floor, (b) 25 floors with 12 occupants per floor, (c) 35 floors with 12 occupants per floor, (d) 45 floors with 12 occupants per floor.

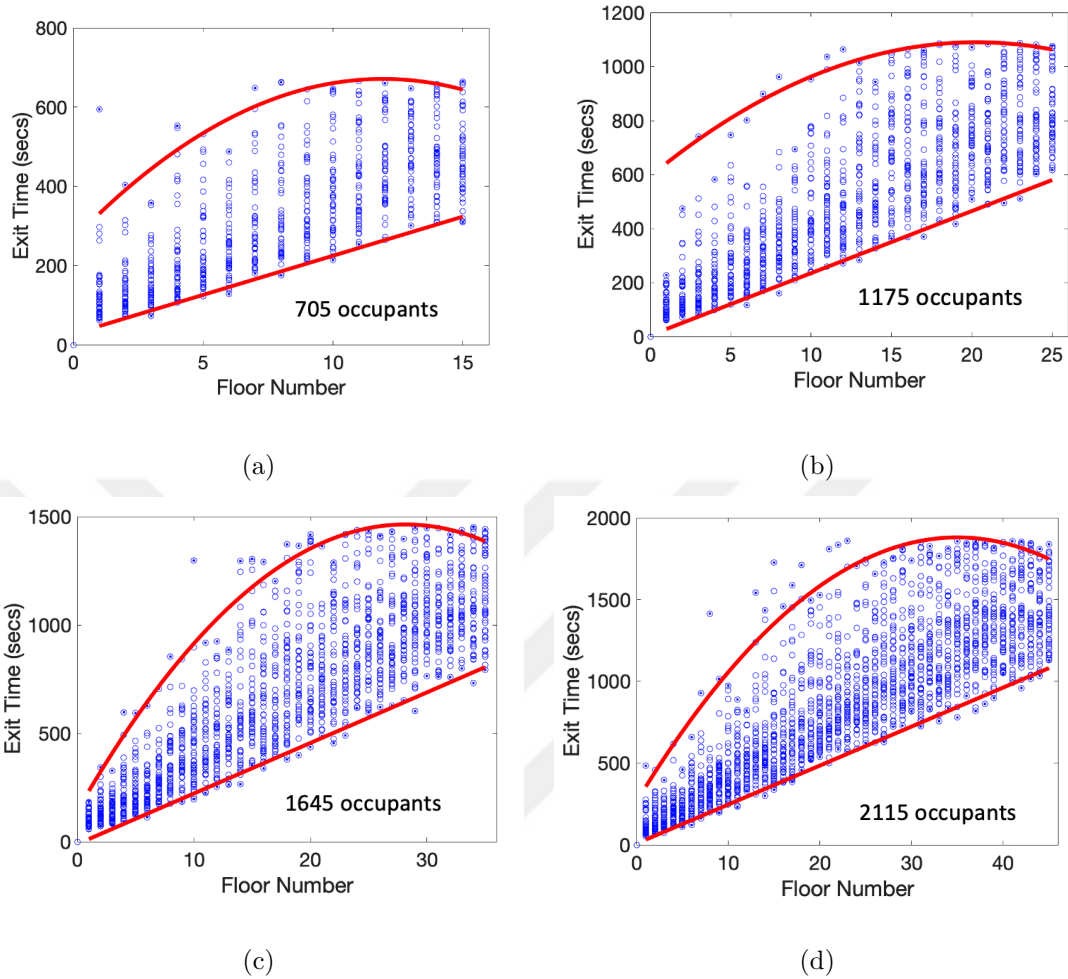


Figure 5.11. Evacuation of occupants from a number of representative residential high-rise building for: (a) 15 floors with 47 occupants per floor, (b) 25 floors with 47 occupants per floor, (c) 35 floors with 47 occupants per floor, (d) 45 floors with 47 occupants per floor.

A MATLAB application is designed to visualize evacuation dynamics during fire emergencies in high-rise residential buildings. The purpose of the app is to simulate evacuation scenarios based on parametric data from multi-floor buildings. The app visualizes occupant movement across floors, enabling stakeholders to analyze evacuation performance for varying building heights and occupant densities.

The app generates time-history graphs representing occupant flow during evacuations. User can adjust the number of floors (15 to 45) and occupant levels (6 to 50) using intuitive controls. The app reads pre-processed simulation data saved in .txt files,

representing evacuation patterns for various building configurations. MATLAB App Designer was utilized to create an interactive graphical user interface (GUI).

MATLAB Architecture MATLAB App Designer facilitates the creation of interactive applications through a component-based architecture that aligns with the Model-View-Controller (MVC) design pattern. This architecture ensures separation between the user interface, underlying data, and event-handling logic, promoting scalability and maintainability. Figure 5.12 illustrates the application.

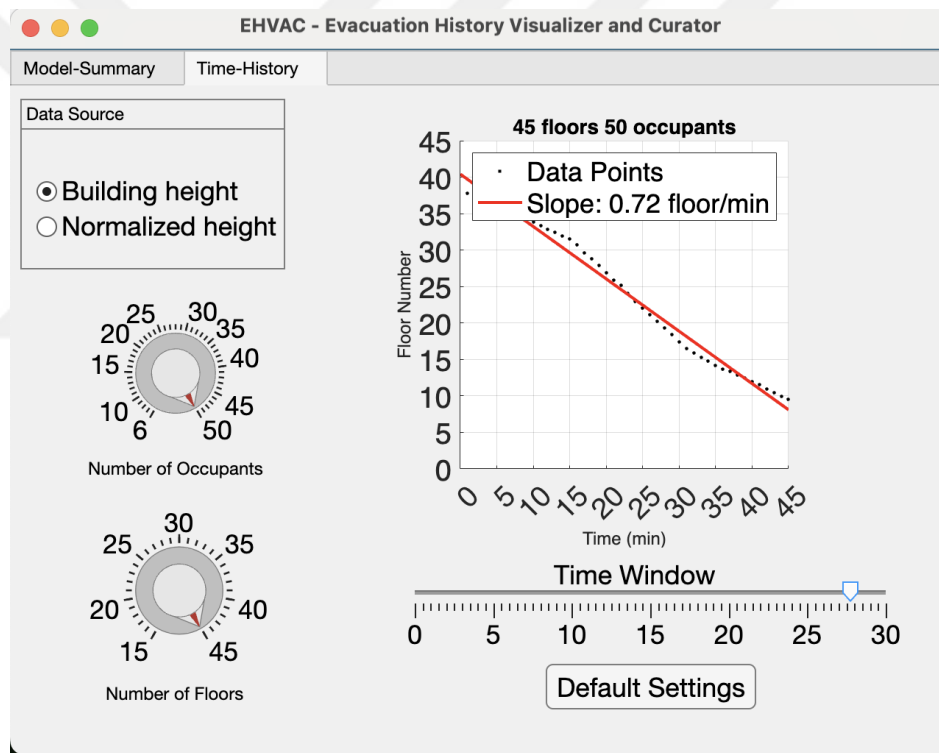


Figure 5.12. Automated time-history MATLAB application.

In Figure 5.13, the floor-by-floor evacuation trajectories are compared across low- and high-occupancy conditions for both mid-rise (15-storey) and high-rise (45-storey) prototypes. In each panel, the scatter of individual floor-clearance times is overlaid by a least-squares linear fit whose slope represents the average evacuation rate in floors per minute. For the 15-storey building, the 10-occupant scenario yields a slope of 0.82 floors/min, whereas increasing the load to 45 occupants reduces the rate to 0.74

floors/min. A similar pattern is observed in the 45-storey case, where light loading (10 occupants per floor) produces a rate of 0.85 floors/min and heavy loading (50 occupants per floor) reduces it to 0.72 floors/min. These results demonstrate that, while evacuation speed is only modestly affected by building height, higher occupant densities consistently depress the mean clearance rate by approximately 8–15 percent.

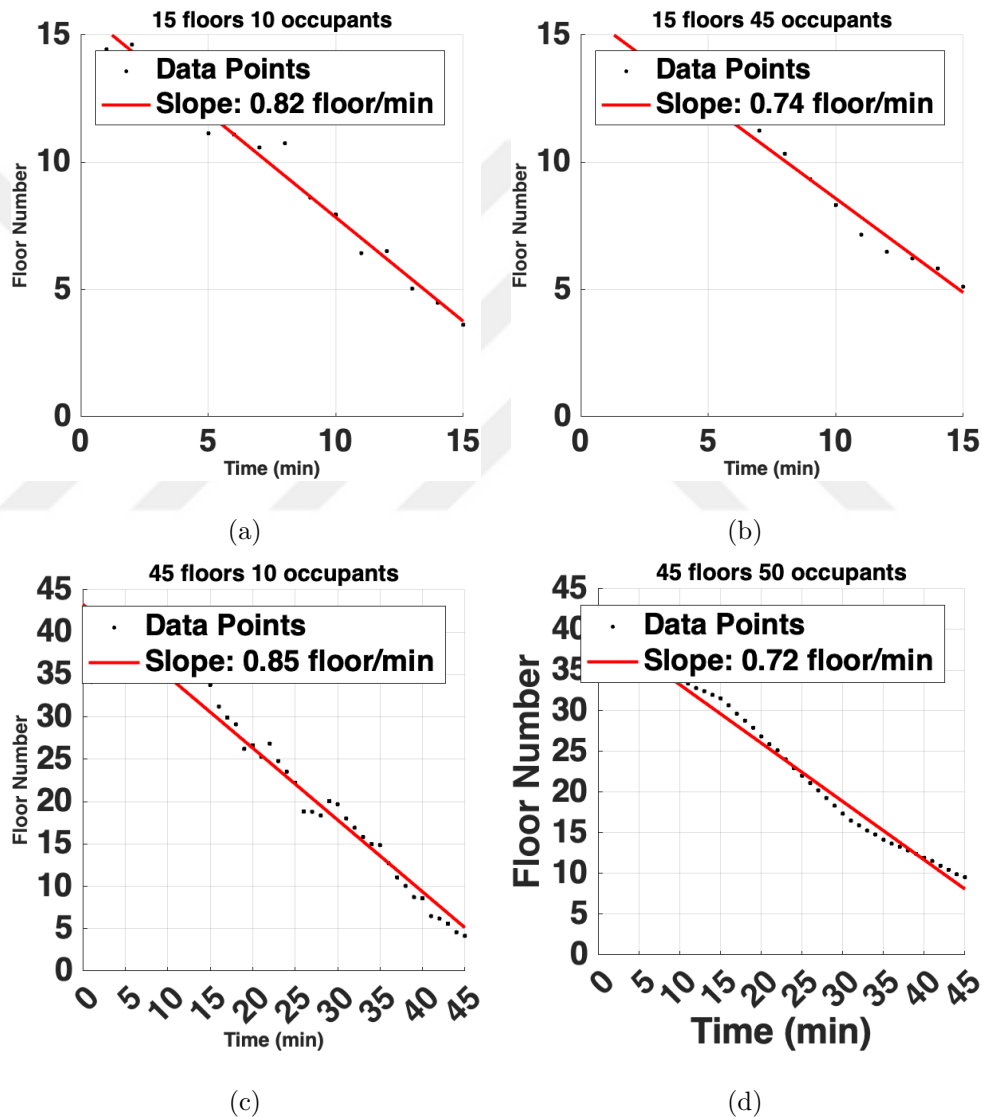


Figure 5.13. Comparison of occupant evacuation flow rate from high-rise residential buildings: (a) 15 floors with 10 occupants per floor, (b) 15 floors with 45 occupants per floor, (c) 45 floors with 10 occupants per floor, and (d) 45 floors with 50 occupants per floor.

6. CITY-SCALE FIRE RESPONSE AND RISK ASSESSMENT

In this chapter, a unified probabilistic framework is applied by integrating occupant evacuation characteristics with fire brigade response performance. Rather than treating response time in isolation, the analysis combines (1) the stairwell tenability threshold time—ASET, as defined in Chapter 5—with (2) the empirical distribution of total evacuation time (TET) and (3) the probabilistic model of fire brigade response intervals (FRT). Under the assumption of statistical independence, the joint probability of evacuation exceeding safe conditions before external intervention is then derived. Section 6.1 details the statistical models for FRT, Section 6.2 defines the threshold events and describes the estimated results, and Section 6.3 applies the methodology to the Istanbul high-rise residential buildings case study.

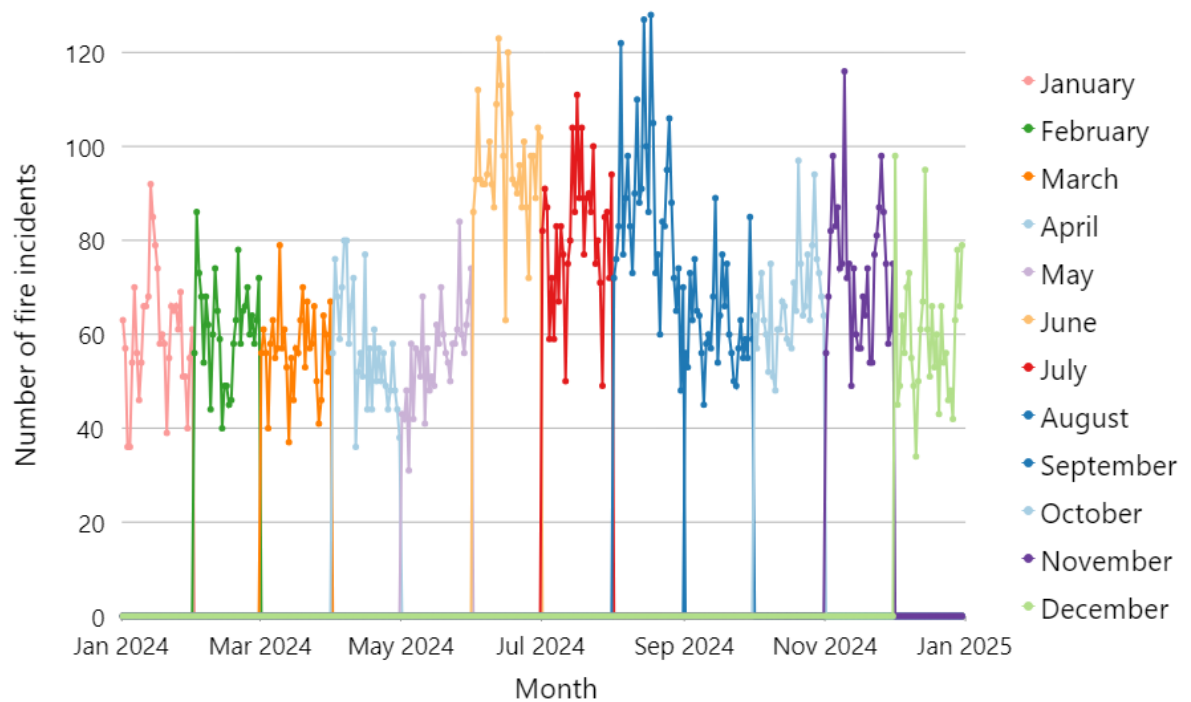


Figure 6.1. Istanbul fire incident record.

6.1. Istanbul Fire Vulnerability

6.1.1. Time Distributions of Fire Brigade Response

The effectiveness of emergency response is fundamentally shaped by the temporal dynamics of fire brigade operations. Figure 6.2 illustrates the probability distribution of turnout time—the interval between alarm receipt and crew departure—for Istanbul’s fire incidents, presented on a logarithmic scale. The histogram displays a distinct right-skewed distribution with a significant concentration around the 100-200 second range, overlaid with a fitted log-normal distribution curve.

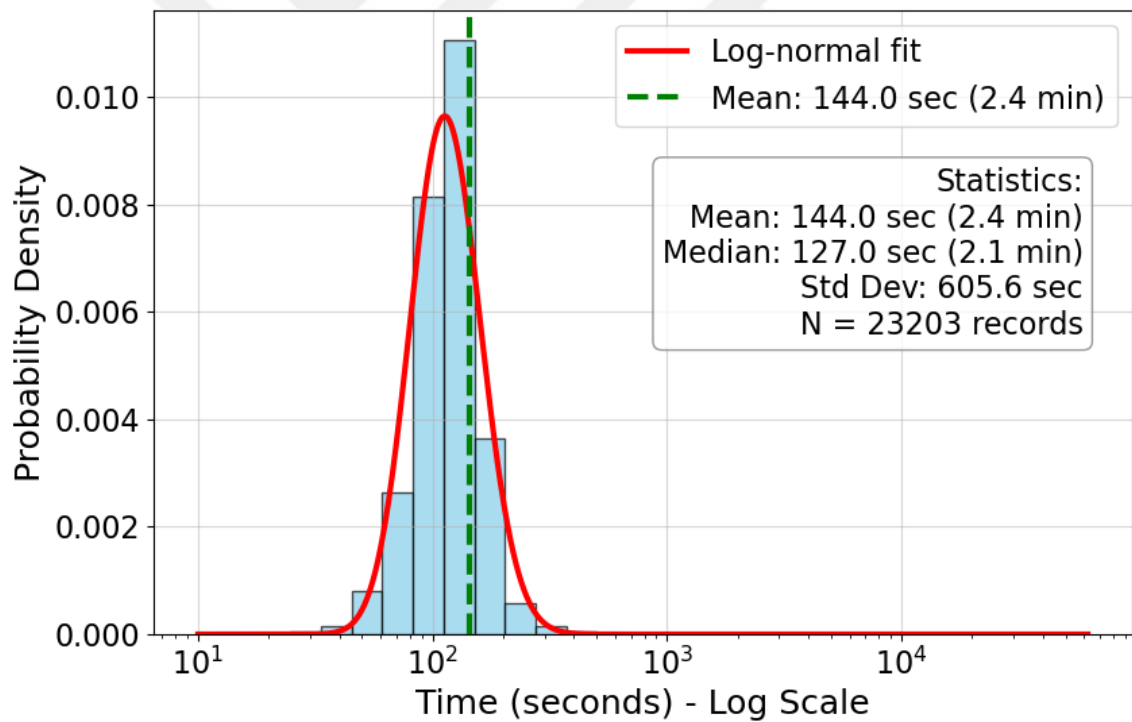


Figure 6.2. Probability distribution of turnout time.

On the other hand, the response time data were characterized by constructing a normalized histogram and fitting a lognormal probability density function. A sample mean of 8.6 minutes and a standard deviation of 3.3 minutes were obtained.

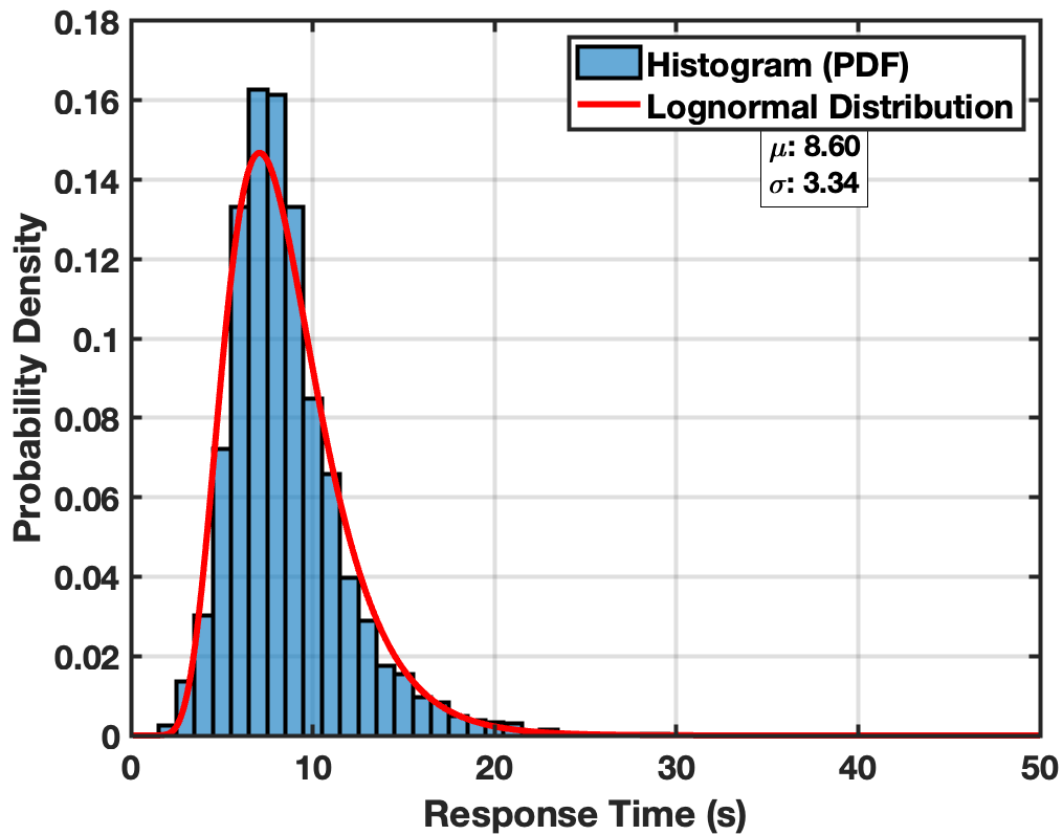


Figure 6.3. Probability distribution of response time.

Analysis of monthly turnout-time distributions reveals consistent performance across all twelve months, with most fire incidents experiencing turnout times concentrated between approximately 80 to 180 seconds (1.3 to 3 minutes), peaking around 120-140 seconds (2-2.3 minutes). This temporal stability suggests that seasonal variations have minimal impact on the initial mobilization capabilities of Istanbul’s fire services. However, the persistent long tail across all months—extending beyond 250 minutes in rare cases—highlights that outlier events with extended response times occur year-round, regardless of seasonal conditions.

These extended-delay incidents likely stem from structural factors such as concurrent alarms, resource limitations, or facility-specific constraints rather than seasonal influences. When considered alongside evacuation timelines from Chapter 5, this turnout-time analysis reveals a critical operational parameter: during the 2-3 minute mobilization interval, high-rise evacuations will have progressed only through the pre-

movement phase and initial stairwell entry, leaving the vast majority of occupants still within the building when crews depart their stations. Table 6.1 gives the mean and standard deviations for TET and FRT.

Table 6.1. Statistical parameters of key time metrics.

	$\mu(min)$	$\sigma(min)$
Total evacuation time	11.5	5.6
Turnout time	2.4	10.1
Response time	8.6	3.3

6.1.2. Seasonal and Diurnal Distribution of Fire Incidents

Understanding temporal patterns in fire occurrence is essential for resource allocation and operational planning. Figure 6.4 depicts the monthly distribution of fire incidents in Istanbul throughout 2024, revealing distinct seasonal patterns in fire occurrence.

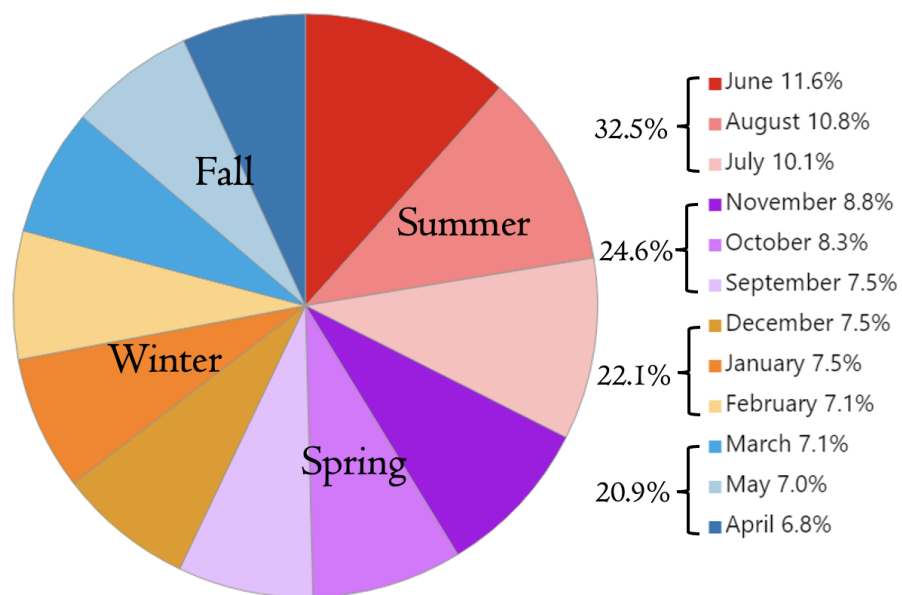


Figure 6.4. Seasonal fire incidents by month.

The figure demonstrates a notable seasonal pattern, with summer months experiencing the highest incidence rates: June leads with 11.6% of annual fires, followed closely by August (10.8%) and July (10.1%). Together, these three summer months account for nearly one-third (32.5%) of all fire incidents, highlighting a significant seasonal concentration. The autumn months of November (8.8%) and October (8.3%) follow as the next most incident-prone periods. In contrast, spring months show the lowest fire occurrence rates, with April recording only 6.8% of annual incidents. The relatively balanced distribution across winter months (December, January, and February), each contributing approximately 7.1-7.5% of incidents, suggests that while seasonal factors clearly influence fire occurrence, a substantial baseline of fire risk persists year-round.

This seasonal variation appears linked to several underlying factors. Higher summer temperatures correlate with increased ignition probability, particularly for electrical and outdoor fires. Additionally, summer vacations alter occupancy patterns and activity profiles within residential structures, potentially introducing unfamiliar usage patterns or temporary occupants less familiar with building systems. The moderate elevation in autumn incidents (October-November) coincides with the transition to heating season, when dormant systems are reactivated, sometimes revealing maintenance deficiencies.

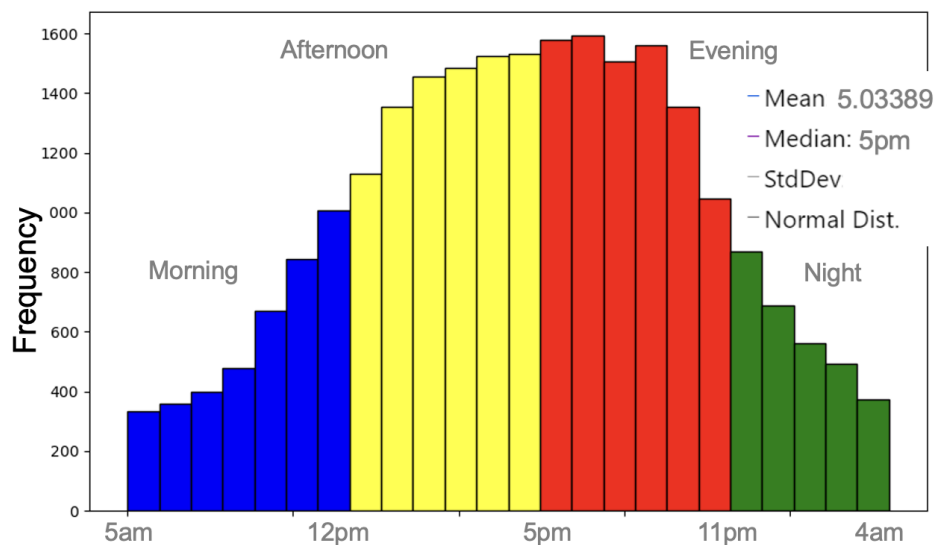


Figure 6.5. Distribution of fire occurrence within the day.

Complementing the seasonal perspective, Figure 6.5 presents the diurnal distribution of fire incidents, highlighting clear temporal patterns throughout a 24-hour cycle. The histogram reveals a symmetrical, nearly normal distribution of fire occurrences across the day, with a fitted normal distribution curve confirming this pattern. Fire incidents steadily increase from early morning (5am), climbing throughout the morning hours and reaching peak frequency during late afternoon and early evening hours, with the highest concentration around 5pm as indicated by the median line. The mean occurrence time is 5.03 hours (5pm), perfectly aligned with the median, reinforcing the symmetrical nature of the distribution. Incident frequencies remain relatively high during evening hours before gradually declining after 11pm, reaching their lowest levels between 4am and 5am.

This diurnal pattern strongly correlates with human activity cycles, with fires being most frequent during peak activity periods and dining hours when cooking, electrical usage, and other fire-triggering activities are common. The distribution demonstrates that fire risk is not static but follows predictable temporal cycles that can be incorporated into resource allocation planning. This temporal understanding is particularly relevant for high-rise residential structures, where maximum occupancy typically coincides with the evening peak in fire incidents, creating a potential compounding effect where maximum evacuation demand occurs during periods of highest service call volume.

Figures 6.5 and 6.6 provide complementary insights into the temporal patterns of fire incidents, examining different dimensions of time-based distribution. Figure 6.6 illustrates the hourly distribution of fire occurrences across each month of the year, revealing consistent diurnal patterns throughout all seasons. Each month exhibits a similar bell-shaped distribution with incidents peaking during afternoon and early evening hours (typically between 12-16 hours), though with varying intensities. Summer months (June, July, and August) show notably higher incident frequencies, with June and August reaching nearly 200 incidents during peak hours, compared to winter months which rarely exceed 100 incidents at their peaks.

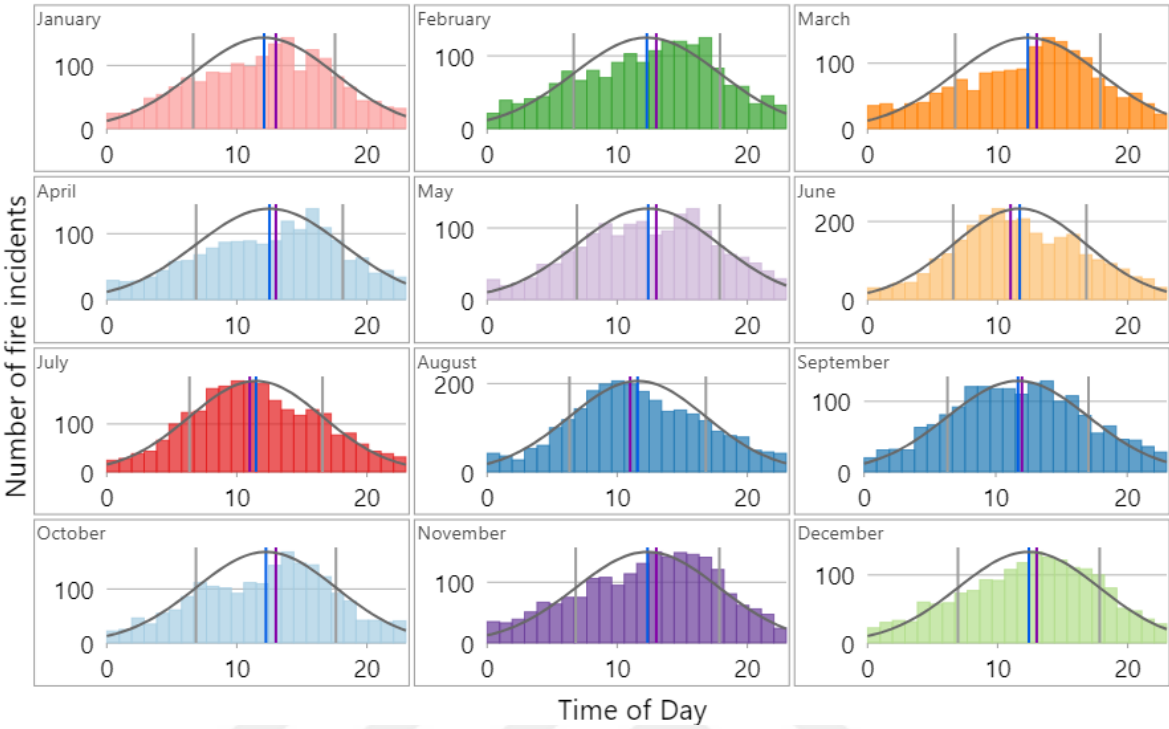


Figure 6.6. Distribution of fire occurrence by month and hour.

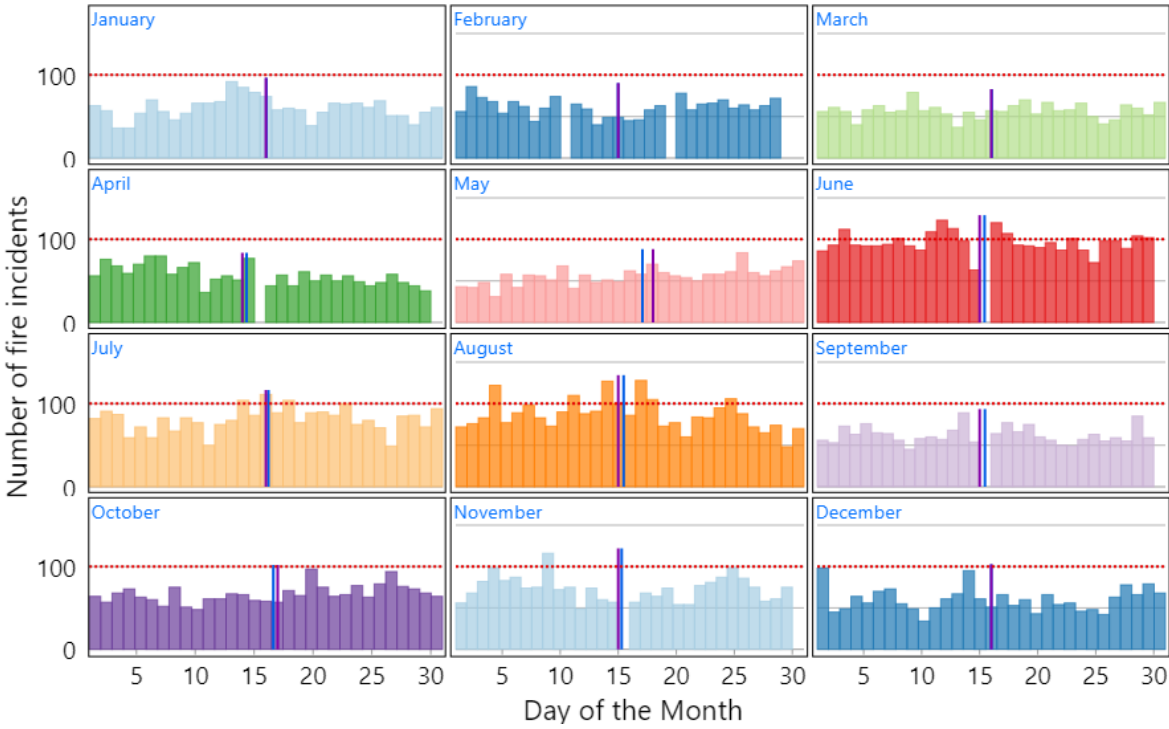


Figure 6.7. Monthly distribution of fire occurrence by day.

Figure 6.7 displays the day-to-day variation in fire incidents across each month, showing relatively consistent daily incident counts within most months, hovering around the 100-incident threshold (marked by the red dotted line). June consistently records the highest daily incident counts, regularly exceeding the 100-incident threshold, while spring months like April show lower daily totals.

For high-rise structures specifically, these temporal patterns suggest that the probability of concurrent high-rise fires—which would strain specialized aerial apparatus and high-rise tactical teams—increases substantially during summer months and evening hours. This concurrency risk directly impacts the effective coverage radius of specialized resources and may necessitate modified dispatch protocols during peak periods to ensure appropriate resource availability for complex high-rise incidents.

6.1.3. Spatial Distribution of Fire Incidents

The spatial distribution of fire incidents reveals crucial patterns that inform resource allocation and risk-mitigation strategies. Figure 6.7 presents the spatial distribution of fire incidents across Istanbul's administrative districts, revealing substantial disparities in fire occurrence patterns throughout the city.

The bar chart displays a clear ascending pattern from left to right, with incident frequencies ranging from fewer than 100 in Adalar (the island district) to nearly 1,800 in Esenyurt, representing an approximately 18-fold difference between the least and most affected districts. A notable pattern emerges where central, densely populated districts and rapidly developing peripheral areas experience significantly higher fire incident frequencies.

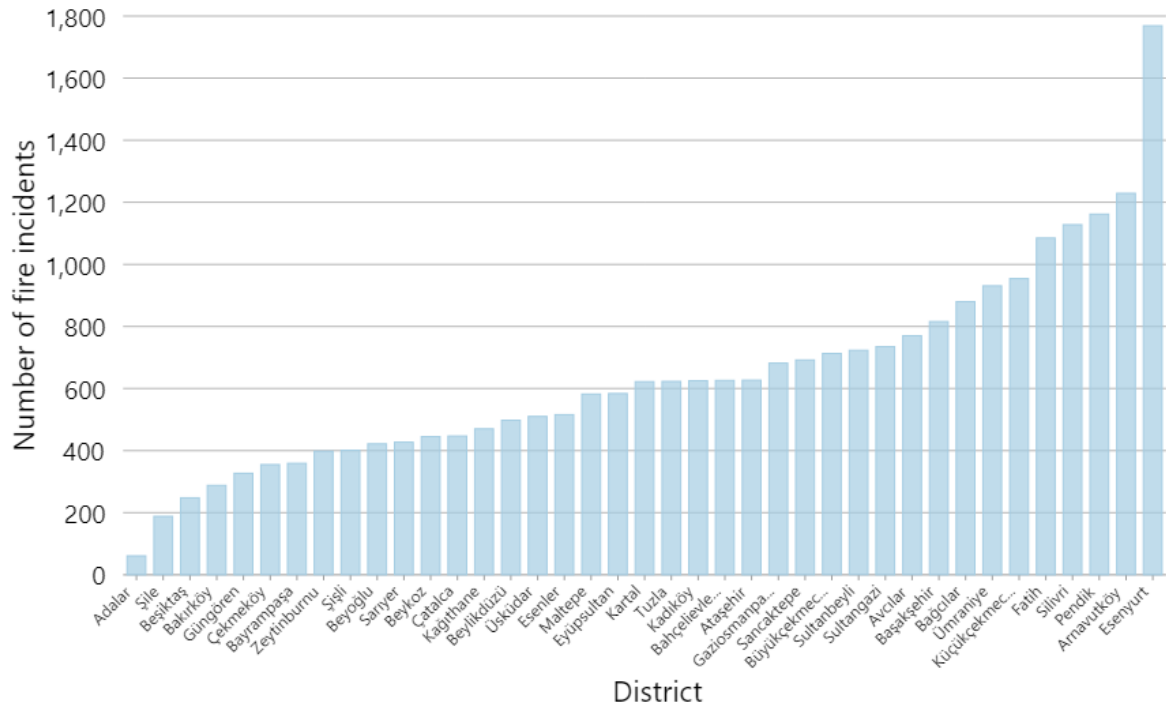


Figure 6.8. Distribution of fire occurrence by District.

The districts showing the highest fire occurrences—Esenyurt, Arnavutköy, Pendik, and Fatih—represent a mix of both historic central neighborhoods (Fatih) and rapidly urbanizing peripheral districts (Esenyurt and Arnavutköy) characterized by intensive construction activity and population growth. Mid-range districts with moderate fire incidents (600-800 occurrences) generally represent more established urban areas with stable infrastructure.

This spatial heterogeneity in fire risk reflects multiple interacting factors:

- (i) Population density: Higher-density areas naturally experience more incidents due to greater human activity and ignition sources.
- (ii) Building age and quality: Historic districts with aging infrastructure and newer peripheral areas with rapid, sometimes less regulated construction both show elevated incident rates.
- (iii) Socioeconomic factors: Districts with lower average income levels often show higher fire incidence rates, potentially reflecting maintenance issues, older appliances, or

higher-density living arrangements.

- (iv) Land use patterns: Mixed-use districts combining residential, commercial, and light industrial uses typically experience more diverse fire causes and higher total incident counts.
- (v) Construction activity: Rapidly developing districts like Esenyurt and Arnavutköy show elevated fire rates, partially attributable to construction-related incidents.

When normalized by building count or population, these district-level patterns provide insight into the underlying risk factors. For high-rise structures specifically, this spatial distribution highlights potential vulnerability hotspots where high incident frequency coincides with high-rise clusters, creating zones where emergency resources may be frequently diverted to other incidents, potentially extending response times to high-rise emergencies.

6.1.4. Fire Risk Mapping

Building on the temporal and spatial analysis of fire incidents, comprehensive fire risk mapping integrates multiple dimensions of vulnerability to identify critical hotspots for targeted intervention.

Risk was defined as

$$\Pr(\text{TET} > \alpha) \cdot \Pr(\text{FRT} > \alpha) \quad (6.1)$$

From the probability distributions of FRT the probability of exceeding α is 0.7483. And since there were 1065 out of 1,167 high-rise residential buildings exceeding the threshold ASET, the risk value for Istanbul Municipality is 68.3%.

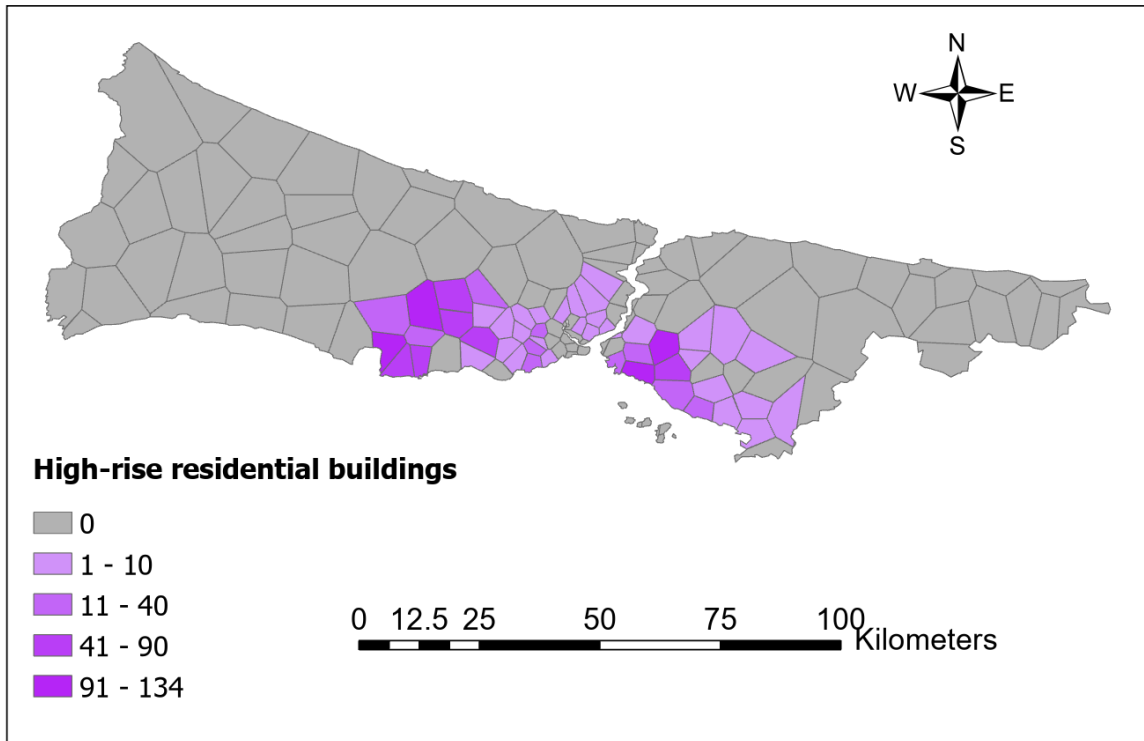


Figure 6.9. Number of high-rise residential buildings per Voronoi cell.

Figure 6.9 presents the spatial distribution of high-rise residential building density across Istanbul by partitioning the province into Voronoi cells around each building centroid; each cell's value corresponds to the total number of high-rise residential buildings within that zone, thereby highlighting where vertical residential development is most and least concentrated throughout the city.

Figure 6.10 represents a comprehensive spatial density analysis of fire incidents across Istanbul, also utilizing Voronoi polygons to visualize the distribution of fire occurrences in each region.

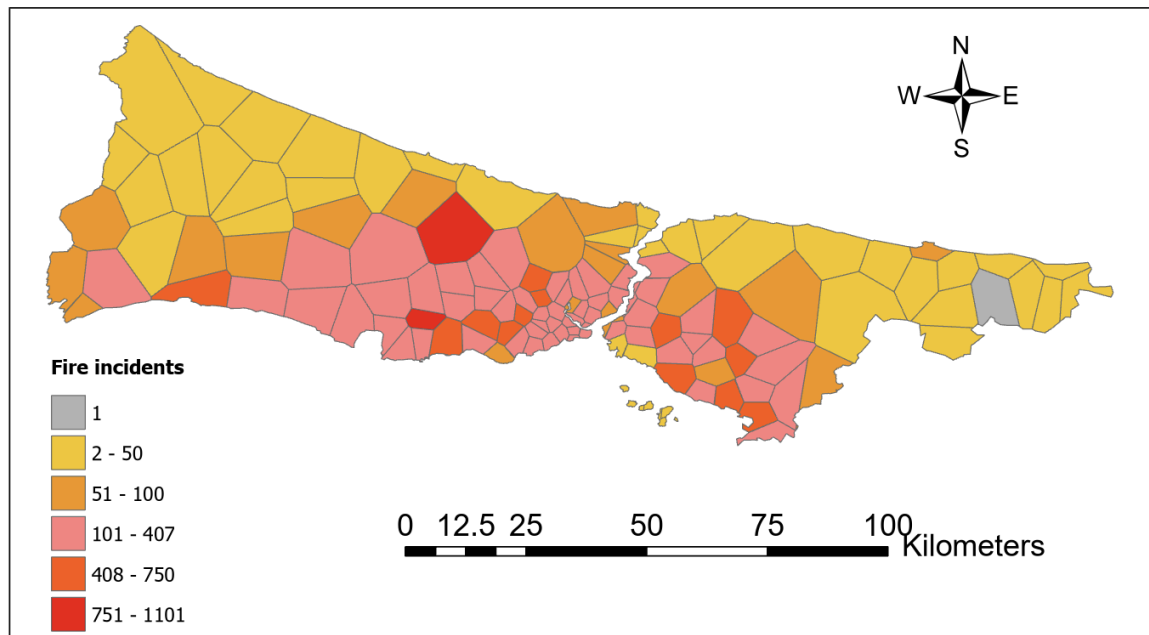


Figure 6.10. Number of fire incidents in Istanbul for each Voronoi cell.

The next step in the analysis is to map the risk profile, to indicate areas of higher fire incidence. In Figure 6.11–Figure 6.14, the Voronoi polygon approach presents the relative risk using all fire incidents of the year and queried residential fire incidents. This spatial analysis offers valuable insights for emergency service planning, suggesting that resources should be strategically concentrated in high-density incident areas while maintaining appropriate coverage in lower-risk zones, and highlighting potential locations where additional fire stations or enhanced response capabilities may be needed to address areas with exceptionally high incident density.

Together, these choropleth maps present pictorial representations of high-rise building fire risk across Istanbul, highlighting the relationship between high-rise residential building locations and fire station distribution.

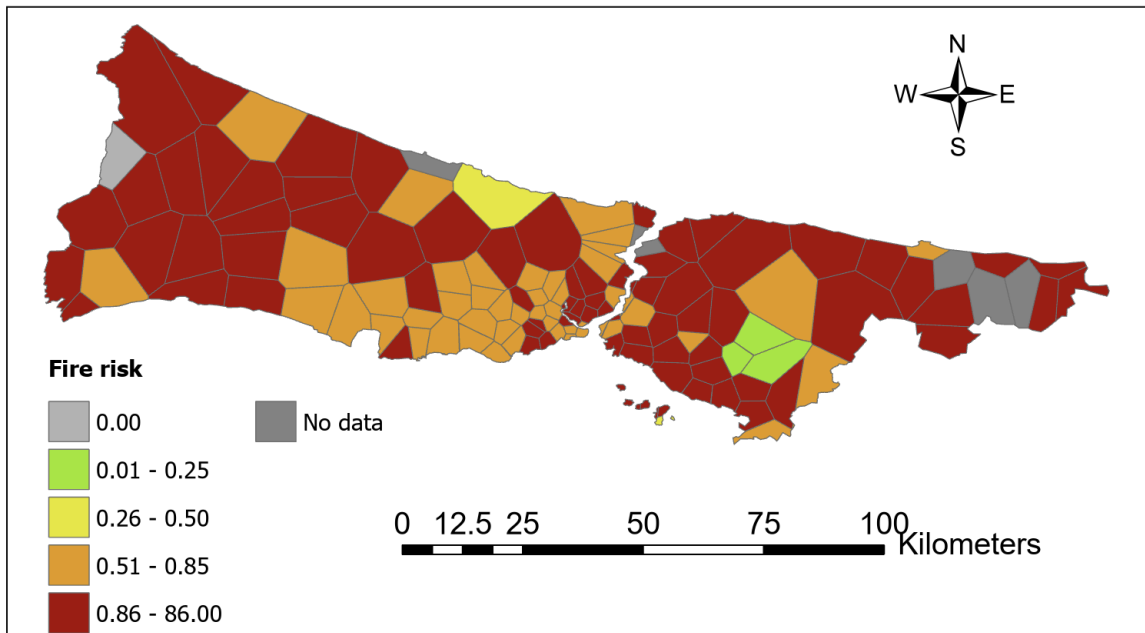


Figure 6.11. Fire risk map of residential buildings in Istanbul based on response to residential fire incidents.

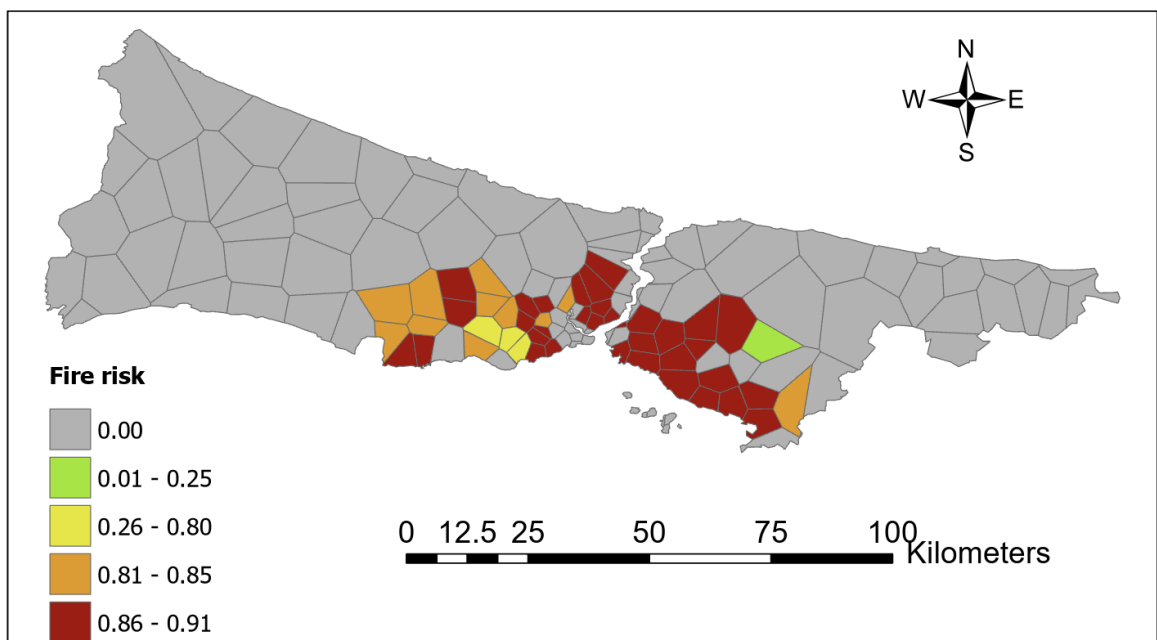


Figure 6.12. Fire risk map of high-rise residential buildings in Istanbul based on response to residential fire incidents in high-rise Voronoi cells.

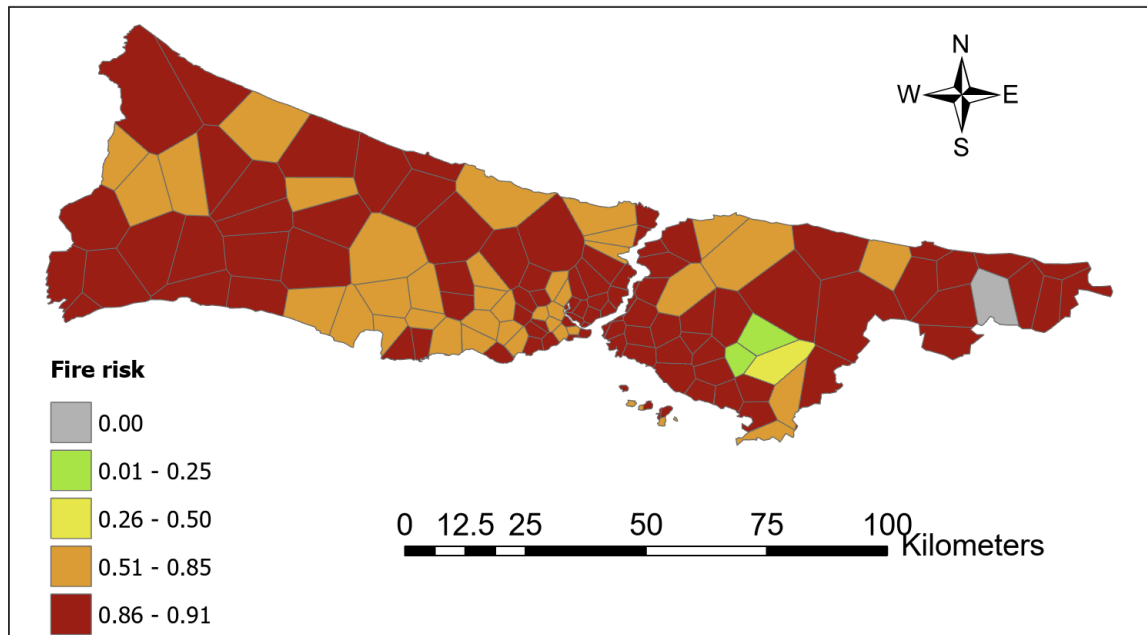


Figure 6.13. Fire risk map of residential buildings in Istanbul based on response to all fire incidents.

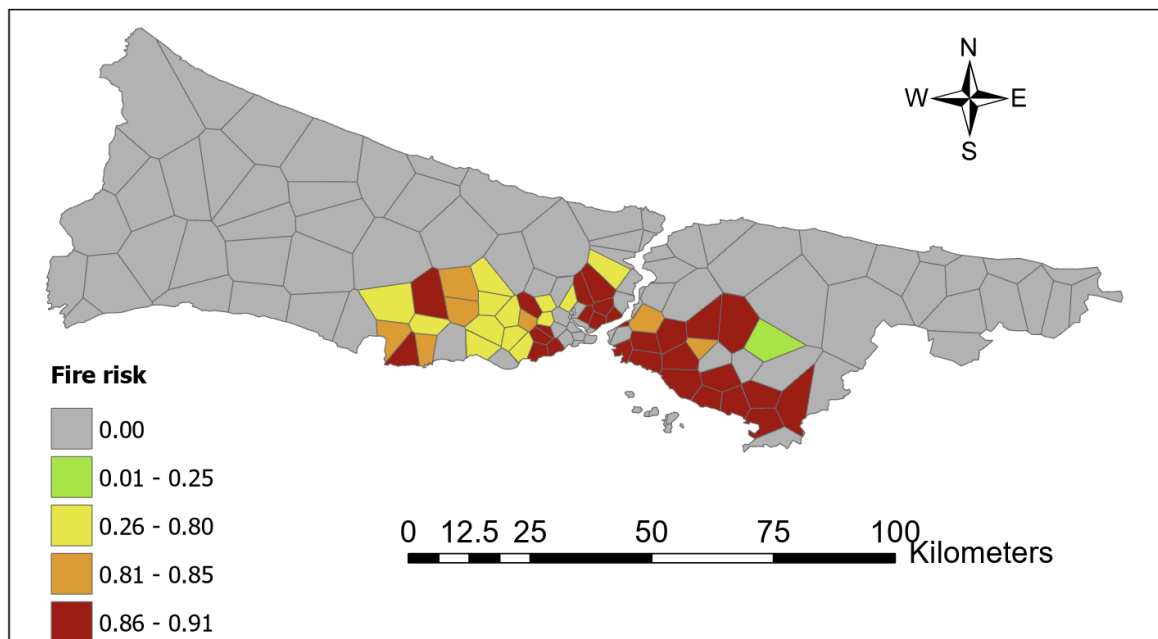


Figure 6.14. Fire risk map of high-rise residential buildings in Istanbul based on response to all fire incidents in high-rise Voronoi cells.

6.2. Network Analysis

Building on the spatial patterns identified in Section 6.1, this section examines the dynamic relationship between fire stations, transportation infrastructure, and high-rise locations through the lens of network analysis. By modeling the city's road system as a connected graph with impedance values that reflect travel constraints, we can quantify emergency-response accessibility more precisely than simple Euclidean distance measures, accounting for the real-world constraints that shape fire-brigade travel times.

Figure 6.15 presents the distribution of travel times between high-rise residential buildings and their closest fire stations under both peak and off-peak traffic conditions, providing a quantitative foundation for assessing service delivery capabilities.

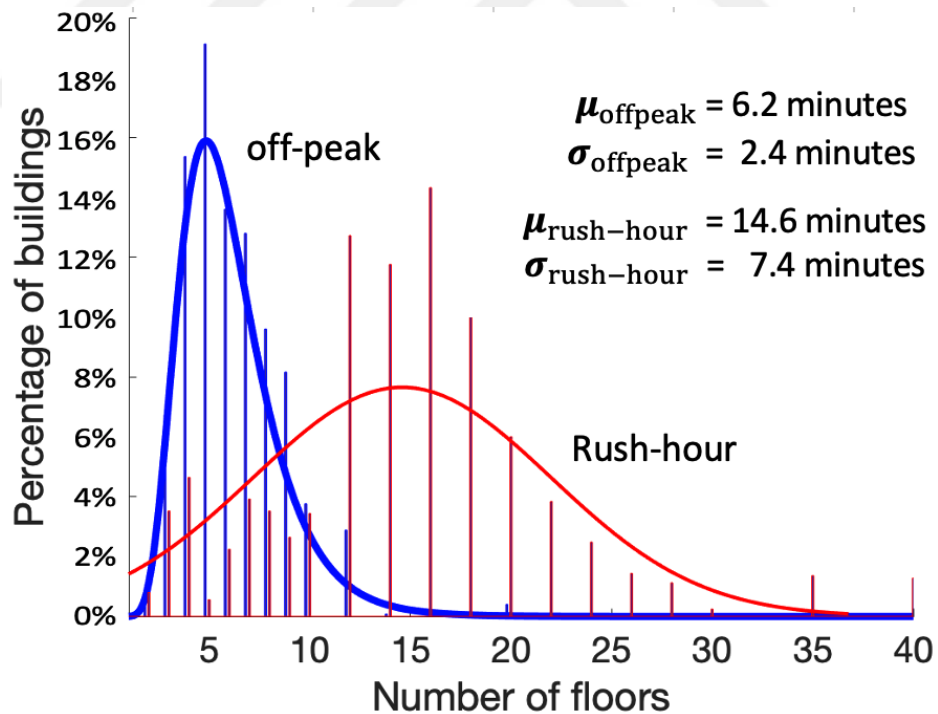


Figure 6.15. Distributions of peak and off-peak travel times between residential high-rise buildings to closest fire stations.

The histogram reveals a bimodal distribution of travel times, with a primary mode centered around 3-4 minutes and a secondary mode near 7-8 minutes. This

pattern suggests two distinct classes of service coverage: primary zones with rapid access (≤ 4 minutes) and secondary zones with moderate access times (5-10 minutes). The distribution also demonstrates significant divergence between peak and off-peak scenarios, with peak-hour congestion substantially shifting the curve rightward and broadening its spread.

Under off-peak conditions, approximately 67% of high-rise buildings fall within the NFPA-recommended 4-minute travel-time threshold, with a median travel time of 3.7 minutes. However, during weekday peak hours, this coverage contracts to only 42%, with the median travel time extending to 5.8 minutes—a 57% increase in response delay. This temporal variation in accessibility creates a dynamic risk landscape where a building’s effective vulnerability fluctuates throughout the day based on ambient traffic conditions.

The long right tail of the distribution further indicates that a small but significant fraction of high-rise buildings (approximately 8% during off-peak and 17% during peak conditions) experience potential travel times exceeding 10 minutes, placing them well beyond recommended service standards. These temporally variable accessibility constraints fundamentally shape the operational environment for emergency response and must be integrated into any comprehensive risk-assessment framework.

Moreover, as shown in Figure 6.16, in the summer months (June, July, and August), fires climb steeply after sunrise and reach much higher midday peaks—often over 200 incidents—before slowly falling off in the afternoon and evening. In the rest of the year, the same daily rise-and-fall pattern happens, but the highest hourly counts are much lower (usually around 120–140), so overall there are far fewer fire calls each hour outside of summer.

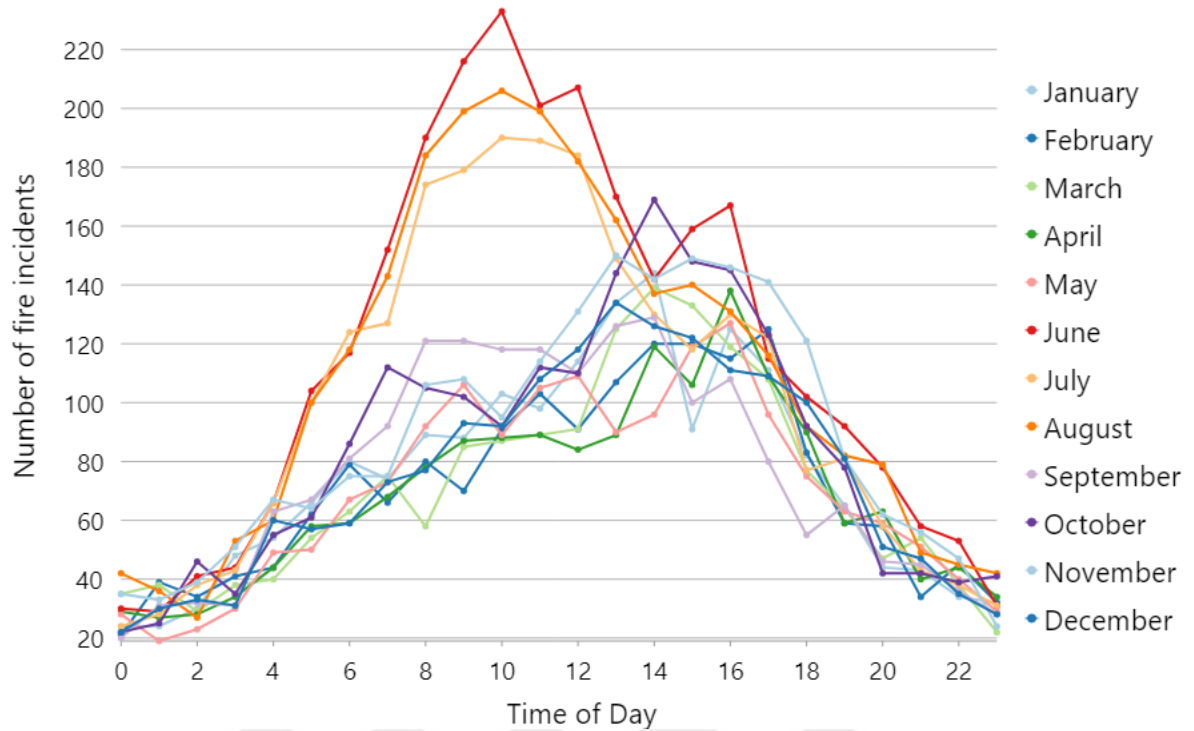


Figure 6.16. Time of Day of Fire Occurrence by Month.

To advance beyond these univariate distributions, two complementary network-analysis methods were employed: (1) service-area analysis to delineate multi-threshold coverage zones around each station, and (2) origin-destination (OD) cost-matrix calculations to determine the minimum network-constrained travel time between each station-building pair.

6.2.1. OD Cost Matrix Analysis

Origin-Destination (OD) cost matrix analysis provides a comprehensive evaluation of the connectivity between all fire stations (origins) and high-rise buildings (destinations) across Istanbul's road network. This method computes the minimum-impedance path between each station-building pair, yielding a matrix of travel times that quantifies the relative accessibility of every high-rise building from each potential responding station.

The OD cost matrix was calculated using ArcGIS Network Analyst, incorporating the digitized road network described in Chapter 4, with travel-time impedances derived

from road segment length, functional classification, and time-of-day speed factors calibrated from historical traffic data. For each high-rise building, the analysis identified the n -nearest fire stations (where $n = 5$) and the associated travel times, enabling both first-due and subsequent-alarm travel-time estimation.

Table 6.1 summarizes the OD cost matrix results, presenting the distribution of network travel times from closest fire stations to high-rise buildings across different time periods and traffic conditions.

Table 6.2. Network travel times from closest fire stations to high-rise buildings.

Time Period	Mean Travel Time (min)	Median Travel Time (min)	90th Per- centile (min)	% Within 4 min	% Within 8 min
Overnight (00:00-06:00)	3.8	3.2	7.9	72%	89%
Morning Peak (07:00-09:00)	6.2	5.5	11.2	38%	71%
Midday (10:00-15:00)	5.1	4.6	9.3	47%	79%
Evening Peak (16:00-19:00)	6.7	5.9	11.8	35%	68%
Evening (20:00-23:00)	4.5	3.9	8.7	58%	84%

The results reveal substantial temporal variation in emergency service accessibility, with mean travel times increasing by up to 76% during peak periods compared to overnight conditions. This temporal oscillation in service coverage means that the same high-rise building faces different vulnerability levels throughout the day, with minimum response capabilities during evening peak periods—which, as shown in Section 6.1.2, coincide with maximum fire incidence rates.

For second-due and third-due units—critical for high-rise incidents requiring multiple apparatus—the temporal constraints are even more pronounced. During peak periods, the mean travel time for second-due units extends to 9.3 minutes, with only 41% arriving within the 8-minute full-alarm-assembly threshold recommended by NFPA standards. This finding has significant implications for resource allocation and dispatch protocols, suggesting that simultaneous dispatch of multiple units may be necessary during peak periods to achieve effective alarm assembly within operational timeframes.

The OD cost matrix was further analyzed to identify patterns of isolation and clustering among high-rise buildings. Hierarchical cluster analysis of travel-time matrices identified 23 distinct high-rise clusters with similar accessibility profiles, highlighting zones where multiple tall buildings share similar response-time constraints. These clusters form natural planning units for specialized resource allocation, as they represent zones where tactical challenges (multiple high-rises with similar response dynamics) coincide with operational constraints (travel-time barriers).

6.2.2. Service Area Analysis

Service area (isochrone) analysis complements the point-to-point OD matrix by delineating continuous coverage zones around each fire station, based on network-constrained travel times. This approach yields isochrone maps—contour lines connecting points of equal travel time—that visualize the spatial reach of emergency services under different temporal thresholds.

Service areas were generated for 4-minute, 8-minute, and 12-minute thresholds, reflecting critical operational benchmarks established in NFPA guidelines. The analysis incorporated detailed network attributes including:

- One-way streets and turn restrictions
- Variable travel speeds based on road classification
- Intersection delays based on control type (signals vs. uncontrolled)

- Time-of-day congestion factors derived from historical traffic data

The service area analysis reveals that while 75% of Istanbul's municipal area falls within the 8-minute response threshold during off-peak conditions, this coverage contracts to 58% during peak periods. More critically, when weighted by built area rather than geographic extent, the effective coverage increases to 83% (off-peak) and 67% (peak), reflecting the concentration of development in areas with better emergency service accessibility.

By combining the OD cost matrix results with service area boundaries, we can identify zones where improved network connectivity would yield the greatest enhancement in emergency response capabilities. In particular, the analysis highlights 17 critical road segments whose congestion disproportionately impacts high-rise accessibility, suggesting that targeted traffic-management interventions on these key corridors could substantially improve emergency service delivery to vulnerable structures.

6.2.3. Optimum Locations of Fire Stations

Based on the spatial distribution of high-rise residential buildings and the locations of current fire stations (Figure 6.17), there are clear coverage gaps in the western and central districts. To address these underserved areas and reduce emergency response times, it is recommended to establish two new fire stations at the locations highlighted in Figure 6.18. Implementing these data-driven siting decisions will align resources with the highest concentrations of high-rise occupancy and enhance overall preparedness.



Figure 6.17. Spatial distribution of high-rise residential buildings and existing fire stations in Istanbul.



Figure 6.18. Proposed additional fire station locations to improve coverage of high-rise clusters.

The optimization analysis also evaluated the coverage improvement achievable through strategic repositioning of mobile resources (e.g., aerial apparatus and specialized high-rise response units) during peak vulnerability periods. By temporarily positioning these resources at six identified staging locations during high-risk time windows (weekday evenings, summer months), response capabilities could be enhanced for 28

These optimization results provide a quantitative foundation for strategic resource-allocation decisions, highlighting zones where targeted infrastructure investments would yield the greatest improvement in emergency service delivery to vulnerable high-rise populations. The findings further emphasize that even modest additions to the current station network—strategically positioned based on network analysis rather than simple geographic distribution—could substantially reduce the number of high-rise buildings that fall outside recommended service thresholds.

6.3. Fire Risk Monitoring Tools

Effective fire disaster preparedness requires not only static risk assessment but also dynamic monitoring capabilities that can track evolving conditions and support real-time decision-making. This section presents the development and implementation of an evacuation time-history analysis application designed to enhance fire risk monitoring for Istanbul’s high-rise buildings

The EHVAC (Evacuation History Visualizer and Curator) application, developed in MATLAB, automates the analysis and visualization of simulation results from the agent-based evacuation models described in Chapter 5. This tool provides an interactive interface for exploring evacuation dynamics across different building configurations and occupancy scenarios, facilitating evidence-based planning and regulatory decision-making.

7. CONCLUSION AND RECOMMENDATIONS

This concluding chapter synthesizes the findings from the occupant evacuation analysis (Chapter 5) and city-scale fire response assessment (Chapter 6), drawing these parallel analyses together into an integrated framework of fire risk for high-rise residential buildings in Istanbul. The research has demonstrated that effective disaster preparedness requires coordinated understanding of building-level evacuation dynamics, hazard evolution as well as urban-scale emergency response capabilities. This chapter expresses the significance of these insights, develops specific recommendations for policy and practice, and outlines directions for future research that could further advance urban fire safety.

7.1. Summary of Findings

The present work has investigated the critical relationship between occupant evacuation and emergency response for high-rise residential buildings in Istanbul, Turkey. Through a methodological approach that bridges micro-scale occupant analysis with macro-scale geospatial analysis, the study has yielded several significant findings that advance our understanding of urban fire risk.

7.1.1. Occupant Evacuation Dynamics

The analysis of evacuation performance for representative high-rise residential buildings revealed several important patterns:

- (i) Height-dependent evacuation rates: Evacuation speed is more strongly influenced by building height than by occupant load, with taller buildings (>30 floors) experiencing systematic degradation in floor clearance rates regardless of occupancy density. This finding challenges common regulatory approaches that focus primarily on population density without adequately accounting for the compound effects

of vertical travel distance.

- (ii) **Queuing threshold behavior:** A critical occupancy threshold (approximately 20-25 occupants per floor) was identified, above which stairwell congestion creates nonlinear increases in evacuation time. This threshold represents a fundamental capacity constraint that cannot be overcome through traditional egress-width calculations alone, suggesting the need for alternative approaches such as phased evacuation for densely populated high-rise structures.
- (iii) **Predictable floor-clearance patterns:** The rate at which successive floors are evacuated follows a linear relationship with building height once queuing conditions are established, with clearance rates ranging from 0.72 to 0.85 floors per minute depending on occupancy conditions. This predictable pattern provides a foundation for tactical planning and resource allocation during emergency response operations.
- (iv) **Impact of environmental degradation:** Smoke conditions significantly impact evacuation performance, with the simulation including fire effects showing a 60% increase in total evacuation time for buildings above 30 floors. This finding highlights the critical importance of smoke management systems and protected egress routes, particularly for taller structures where extended evacuation times create prolonged exposure to deteriorating conditions.

These building-level findings demonstrate that evacuation performance is governed by complex interactions between structural configuration, occupant characteristics, and environmental conditions.

7.1.2. Emergency Response Capabilities

The city-scale analysis of fire service response capabilities revealed complementary insights regarding the urban context within which high-rise evacuation occurs:

- (i) **Spatial coverage disparities:** Significant spatial variations in emergency service coverage were identified, with network analysis revealing that only 67% of high-

rise buildings fall within the NFPA-recommended 4-minute travel-time threshold during off-peak conditions, decreasing to 42% during peak traffic periods. This spatial disparity creates fundamental differences in the effective risk profile of otherwise similar buildings based solely on their location within the urban network.

- (ii) Temporal response variations: Emergency response capabilities exhibit pronounced temporal cycles, with response times increasing by 40-65% during peak traffic periods compared to overnight conditions. This temporal pattern creates a dynamic risk landscape where a building's effective vulnerability fluctuates throughout the day, week, and season.
- (iii) Seasonal incident patterns: Fire incidents show distinct seasonal variations, with summer months (June-August) accounting for nearly one-third (32.5%) of annual incidents. This seasonal concentration creates periods of elevated system-wide risk when higher incident frequency coincides with potentially stretched emergency resources.
- (iv) Incident clustering: The spatial distribution of fire incidents reveals significant clustering, with certain districts experiencing up to 18 times more incidents than others. This non-uniform distribution highlights the need for spatially targeted interventions rather than uniform citywide approaches.
- (v) Network vulnerability: The road network analysis identified at least 17 critical corridors where congestion disproportionately impacts emergency access to high-rise clusters. These network bottlenecks represent priority targets for traffic management interventions to enhance emergency response reliability.

The integration of these response-focused findings with the evacuation analysis reveals the critical relationship between building clearance times and fire service arrival. For 73% of Istanbul's high-rise residential buildings, evacuation would still be in progress when first responders arrive, highlighting the importance of coordinated approaches that account for ongoing occupant movement during firefighting operations.

7.1.3. Integrated Fire Risk

The synthesis of evacuation and response analyses yielded a comprehensive understanding of combined fire risk distribution across Istanbul:

- (i) Building-level vulnerability index: The multi-factor vulnerability assessment (integrating evacuation demand, response capability, building height, occupant load, and historical incident density) identified 178 high-rise buildings (15.3% of the total inventory) with vulnerability scores exceeding 7.5, representing structures with critical combinations of evacuation challenges and response limitations.
- (ii) District-level risk patterns: The aggregation of building-level risk to district scale revealed distinct spatial patterns, with emerging high-rise districts generally showing higher vulnerability than established areas. This pattern suggests that infrastructure development has not kept pace with vertical growth in rapidly developing zones.
- (iii) Optimization opportunities: Network analysis and site suitability assessment identified five priority zones where strategically positioned new fire stations could substantially improve coverage for vulnerable high-rise clusters, with the greatest impact potential in rapidly developing peripheral districts.

These integrated findings provide a foundation for evidence-based planning and policy development, highlighting specific areas, buildings, and conditions where targeted interventions would yield the greatest improvement in overall safety outcomes.

7.2. Research Significance

This work makes several significant contributions to the fields of fire safety engineering, emergency planning, and urban resilience:

7.2.1. Methodological Advancement

The research demonstrates a novel methodological approach that bridges traditionally separate domains of investigation: building-level evacuation dynamics and urban-scale emergency response. By developing a framework that integrates agent-based evacuation modeling with GIS-based network analysis, the study provides a more comprehensive assessment of fire risk than either approach could achieve in isolation. This methodological integration offers a template for future research that seeks to understand complex urban safety systems as interconnected wholes rather than isolated components. The development of specific analytical tools—including the EHVAC evacuation visualization application, the spatial decision support system for resource allocation, and the vulnerability dashboard—further advances the practical application of these methodological approaches. These tools transform complex analytical outputs into accessible decision-support formats that can inform policy and practice across diverse stakeholder groups.

7.2.2. Empirical Contribution

The study provides the first comprehensive assessment of high-rise fire risk for Istanbul—a rapidly verticalizing global city with a complex urban morphology. By analyzing the entire inventory of high-rise residential buildings ($n = 1,167$) across the metropolitan area, the research offers unprecedented insight into the spatial and temporal distribution of fire vulnerability in this critical urban context. The empirical findings challenge several conventional assumptions about fire safety. The identification of queuing thresholds in evacuation performance, the quantification of temporal response variations, and the mapping of evacuation-response relationships all provide new empirical insights that can inform both theoretical understanding and practical application in the field.

7.2.3. Policy and Planning Implications

The research has significant implications for urban fire safety policy and planning, particularly in rapidly developing cities experiencing vertical growth. The findings highlight the need for integrated approaches that address both building-level safety systems and urban infrastructure development in a coordinated manner. The identification of specific vulnerability hotspots, critical urban regions, and priority zones for infrastructure development provides actionable intelligence for targeted interventions that can enhance urban resilience within existing resource constraints. The research also demonstrates the value of dynamic, risk-based approaches to emergency planning—moving beyond static regulatory requirements to develop adaptive systems that respond to the temporal and spatial variations in urban risk landscapes. This shift from prescriptive to performance-based planning offers a more nuanced and effective approach to managing fire risk in complex urban environments.

7.2.4. Theoretical Contribution

At a theoretical level, the research advances our understanding of urban resilience by conceptualizing fire safety as an emergent property of coupled human-infrastructure systems. By examining how building dynamics, human behavior, urban form, and emergency infrastructure interact across multiple scales, the study contributes to a more sophisticated theoretical framework for understanding urban vulnerability and resilience. The research particularly advances the concept of "dynamic vulnerability"—recognizing that urban risk is not a static condition but fluctuates across temporal scales from hours to seasons. This temporal dimension of risk has been undertheorized in previous work, which has largely focused on spatial vulnerability patterns without adequately addressing how those patterns evolve through time. The findings regarding temporal variations in both incident occurrence and response capability provide a foundation for more nuanced theoretical models of urban risk that incorporate this dynamic dimension.

7.3. Recommendations for High-rise Residential Buildings and Fire Emergency Response in Istanbul

Based on the integrated findings of this research, several specific recommendations are proposed to enhance fire disaster preparedness for Istanbul's high-rise residential buildings:

7.3.1. Building-Level Interventions

- (i) **Stratified Evacuation Requirements:** Implement height-dependent evacuation protocols that recognize the qualitatively different challenges faced by buildings of different scales. For buildings exceeding 30 floors, implement mandatory phased evacuation systems that prevent stairwell overloading and maintain evacuation flow rates below critical congestion thresholds.
- (ii) **Enhanced Smoke Management:** Prioritize retrofitting of smoke control systems in buildings identified as "vulnerable", where extended evacuation times create prolonged exposure to potential smoke conditions. These systems should focus particularly on stairwell pressurization to maintain tenable conditions in primary egress routes.
- (iii) **Occupant Education Programs:** Develop targeted education campaigns for residents of high-vulnerability buildings, focusing on reducing pre-movement delays, proper evacuation procedures, and recognition of alarm signals. These programs should be customized to address building-specific evacuation challenges rather than applying generic approaches.
- (iv) **Pre-Incident Planning Requirements:** Establish mandatory pre-incident planning for all buildings with vulnerability scores exceeding a threshold value, ensuring that both building management and fire departments have detailed, building-specific strategies for coordinating evacuation and firefighting operations.
- (v) **Communication System Enhancements:** Implement requirements for enhanced emergency communication systems in buildings within identified vulnerability hotspots, ensuring clear notification and ongoing communication with occupants

during evacuation. These systems should support real-time information delivery that can adapt to evolving incident conditions.

7.3.2. Emergency Response Optimization

- (i) **Strategic Resource Allocation:** Implement the optimized station location plan identified in Section 6.2.3, establishing new fire stations in the five priority zones to enhance coverage for vulnerable high-rise clusters. This strategic infrastructure development would reduce response times for 217 currently underserved high-rise buildings.
- (ii) **Dynamic Resource Positioning:** Develop a mobile resource deployment strategy that positions specialized apparatus (aerial platforms, high-rise response units) at identified staging locations during periods of elevated risk (summer evenings, special events). This temporal adaptation would improve response capabilities when they are most critically needed.
- (iii) **Traffic Priority Systems:** Implement emergency vehicle priority systems along the critical regions identified in the network analysis, ensuring reliable emergency access during congested periods. These priority systems could include dedicated lanes, signal preemption, or congestion-bypassing infrastructure.
- (iv) **Cross-Strait Response Capabilities:** Establish specialized marine-transported rapid response teams to address vulnerability zones along both Bosphorus shorelines, reducing dependence on congested bridge crossings during emergency response. These teams should be equipped with lightweight, portable equipment suitable for initial high-rise firefighting operations.
- (v) **Tactical Protocol Development:** Develop area-specific tactical protocols for the five vulnerability hotspots, accounting for the unique challenges of each zone. These protocols should address the specific evacuation-response relationships prevalent in each area, ensuring coordinated operations that maximize effectiveness.

7.3.3. Monitoring and Information Systems

- (i) Integrated Risk Monitoring Platform: Implement the fire vulnerability dashboard described in Section 6.4 as a citywide platform for coordinating risk monitoring across organizational boundaries. This system should provide tailored information to different stakeholder groups while maintaining a common operational picture.
- (ii) Real-Time Building Information Access: Develop a digital repository of building information for all high-rise structures, accessible to emergency responders via mobile devices. This system should include critical details such as floor plans, evacuation routes, fire protection systems, and potential hazards.
- (iii) Traffic-Aware Response Routing: Integrate real-time traffic data into emergency dispatch systems, enabling dynamic route optimization that accounts for current congestion patterns. This capability would reduce the impact of traffic variability on response performance.
- (iv) Temporal Staffing Adjustments: Modify staffing and apparatus deployment schedules to align with temporal risk patterns, particularly increasing resources during summer evenings when both incident frequency and evacuation challenges are highest. This temporal matching of resources to risk would enhance system-wide efficiency.
- (v) Early Warning Integration: Develop data-sharing protocols between building fire alarm systems and municipal emergency dispatch, reducing notification delays and improving response-time performance. This integration would address the critical initial phase of the emergency timeline when seconds can significantly impact outcomes.

7.3.4. Policy and Regulatory Recommendations

- (i) Risk-Based Inspection Prioritization: Restructure fire inspection protocols to focus resources on the buildings with highest vulnerability scores, ensuring more frequent and detailed examination of critical structures. This approach would maximize the impact of limited inspection resources.

- (ii) **Adaptive Building Code Requirements:** Develop location-specific building code enhancements for high-rise structures in vulnerability hotspots, addressing the particular challenges of different urban contexts. These enhanced requirements would compensate for limitations in emergency response capabilities through improved building resilience.
- (iii) **Development Impact Assessment:** Implement mandatory fire-service impact assessments for new high-rise developments, ensuring that vertical growth is accompanied by proportionate enhancements in emergency infrastructure. This proactive approach would prevent the emergence of new vulnerability hotspots as the city continues to develop.
- (iv) **Interagency Coordination Framework:** Establish a formal coordination mechanism between municipal planning, building regulation, traffic management, and emergency services, ensuring that fire safety considerations are integrated into broader urban development processes. This cross-sectoral approach would address the multidimensional nature of fire risk.
- (v) **Performance-Based Compliance Options:** Develop alternative compliance pathways for existing high-risk buildings, allowing performance-based solutions that achieve safety objectives through means other than physical retrofitting where such modifications are impractical. This flexible approach would encourage safety improvements in challenging contexts.

These recommendations provide a structured approach to enhancing fire safety for Istanbul's high-rise residential buildings, targeting interventions at building, operational, and policy levels. By integrating these complementary strategies, significant improvements in overall system resilience could be achieved, even within existing resource constraints.

7.4. Future Research

While this dissertation has advanced our understanding of high-rise fire risk in urban contexts, several promising directions for future research emerge from this work:

7.4.1. Enhanced Evacuation Modeling

- (i) **Heterogeneous Population Models:** Develop more sophisticated agent-based evacuation models that incorporate greater demographic heterogeneity, including age distributions, mobility limitations, and behavioral variations. These enhanced models would provide more realistic simulations of evacuation dynamics in residential settings where population diversity is significant.
- (ii) **Adaptive Evacuation Behavior:** Investigate how occupant decision-making evolves during extended evacuation scenarios, incorporating dynamic route choice, rest periods, and social interactions. This research would address the limitations of current models that assume relatively static behavioral patterns throughout the evacuation process.
- (iii) **Elevator Evacuation Strategies:** Explore the potential of controlled elevator evacuation as a complement to stairway egress, particularly for ultra-tall buildings where vertical travel distances create significant challenges. This research could identify optimal combinations of elevator and stair usage that maximize overall evacuation efficiency.
- (iv) **Environmental Feedback Effects:** Develop integrated fire-evacuation models that capture the dynamic interaction between fire development, smoke movement, and occupant behavior. This research would provide more accurate predictions of evacuation performance under deteriorating environmental conditions.
- (v) **Validation Studies:** Conduct empirical validation of evacuation models through controlled experiments, drills, and post-incident analysis of actual evacuation events. This research would strengthen the empirical foundation of evacuation simulations and improve their predictive accuracy.

7.4.2. Emergency Response Analysis

- (i) **Real-Time Network Modeling:** Develop methods for incorporating real-time traffic data into emergency response modeling, enabling dynamic prediction of travel times and route optimization. This research would advance our understanding

of temporal variations in emergency service accessibility beyond the static or time-period-based approaches used in current practice.

- (ii) **Multi-Hazard Response Capabilities:** Extend the network analysis methodology to address multiple simultaneous hazards, particularly examining how post-earthquake conditions impact fire response capabilities. This research would provide insight into cascading vulnerabilities that emerge during complex disaster scenarios.
- (iii) **Resource Allocation Optimization:** Develop more sophisticated algorithms for optimizing the spatial and temporal allocation of emergency resources across complex urban environments. This research would advance beyond current p-median approaches to incorporate dynamic risk factors, resource interdependencies, and operational constraints.
- (iv) **Tactical Decision-Making:** Investigate how emergency responders make tactical decisions during high-rise incidents, developing cognitive models that could inform both training programs and decision-support tools. This research would address the human factors dimension of emergency response that complements the technical infrastructure analysis.
- (v) **Cross-Jurisdictional Coordination:** Examine how multiple emergency agencies coordinate during complex incidents that cross jurisdictional boundaries, identifying organizational structures and information-sharing mechanisms that optimize collaborative response. This research would address the governance challenges that often affect large-scale emergency operations.

7.4.3. Integrated Urban Fire Safety

- (i) **Digital Twin Development:** Create integrated digital twins of urban areas that combine building information models, transportation networks, population dynamics, and emergency resources into a unified simulation environment. This research would enable more holistic modeling of urban fire safety as an emergent property of interacting systems.

- (ii) **Climate Change Impacts:** Investigate how changing climate conditions may affect urban fire risk profiles, including potential increases in ignition sources, alterations to response capabilities, and modifications to building performance. This research would provide a foundation for climate-adaptive fire safety planning.
- (iii) **Socioeconomic Dimensions:** Explore the relationship between socioeconomic factors and fire risk more comprehensively, examining how social vulnerability interacts with physical infrastructure to shape overall risk profiles. This research would broaden the conception of fire risk beyond technical parameters to incorporate social dimensions.
- (iv) **Longitudinal Vulnerability Tracking:** Develop methods for tracking urban fire vulnerability over time, creating observatories that monitor how risk profiles evolve with urban development, infrastructure changes, and population shifts. This research would provide insight into the dynamic nature of urban fire risk across longer temporal scales.
- (v) **Transferability Analysis:** Examine how the methodological approach developed in this dissertation could be applied and adapted to different urban contexts, identifying which components are generalizable and which require local calibration. This research would extend the impact of the current work to diverse global cities facing similar challenges.

These future research directions would build upon the foundation established in this dissertation, advancing our understanding of urban fire safety across multiple dimensions. By pursuing these complementary lines of inquiry, researchers could further enhance the evidence base for policy and practice in this critical domain of urban resilience.

7.5. Concluding Remarks

This dissertation has demonstrated that effective fire disaster preparedness for high-rise residential buildings requires an integrated understanding of both evacuation dynamics and emergency response capabilities. By bridging these traditionally separate domains through a combined methodological approach, the research has yielded insights

that would not be apparent from either perspective in isolation. The findings reveal significant spatial and temporal variations in fire risk across Istanbul, with distinct vulnerability hotspots emerging from the interaction between building characteristics, urban context, and emergency infrastructure. These patterns highlight the need for targeted interventions that address both building-level safety systems and urban emergency infrastructure in a coordinated manner. As cities worldwide continue to experience vertical growth, understanding the complex relationship between building evacuation and emergency response becomes increasingly critical. The methodological approach and empirical findings presented in this dissertation provide a foundation for evidence-based planning and policy development that can enhance urban resilience in the face of this evolving challenge. By implementing the recommendations outlined in this chapter and pursuing the identified directions for future research, significant improvements in fire safety for high-rise residential buildings could be achieved. These enhancements would not only reduce potential casualties and property damage from individual incidents but would also strengthen the overall resilience of urban systems to fire-related disasters. Finally, population density dataset, derived from the Turkish Statistical Institute (TÜİK), can provide fine-grained spatial distributions of residents, including detailed age distributions. This dataset facilitates precise assessments of potential occupant vulnerability and supports demographic normalization of risk assessment. In conclusion, this research advances our understanding of urban fire risk as a complex, dynamic phenomenon emerging from the interaction of multiple systems across different scales. By adopting this integrated perspective and developing evidence-based strategies that address vulnerability at both building and urban scales, cities like Istanbul can enhance their resilience to fire disasters and create safer living environments for residents of high-rise buildings. Furthermore, statistical distribution of actual occupancy rather than standard density assumptions. Residential fires different in terms of fire characteristics and origins can also be looked into.

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APPENDIX A: BUILDING EVACUATION SYSTEMS DESIGN

The design of building evacuation systems represents one of the most critical aspects of fire safety engineering, with implications that extend far beyond mere regulatory compliance. Throughout history, the evolution of egress design has been shaped by a complex interplay of tragic events, technological innovations, scientific discoveries, and regulatory responses. Understanding this historical development is essential for contemporary fire safety professionals, as it reveals not only how current standards came to be, but also the underlying principles that continue to guide modern evacuation system design.

The regulatory landscape surrounding building evacuation has evolved from informal industry practices to comprehensive, scientifically-based codes and standards. This historical perspective is particularly valuable because many of the fundamental principles established decades ago continue to influence contemporary design practice. The geometric relationships for stair design, the basic concepts of exit capacity calculation, and the organizational structures that develop and maintain safety standards all trace their origins to key moments in the timeline presented below. By understanding these historical foundations, fire safety engineers can better appreciate the rationale behind current requirements and make more informed decisions when applying or extending these principles to novel situations.

Table A.1 shows the historical timeline of egress systems design, which chronicles the major milestones in egress design development, highlighting the key breakthroughs, their immediate consequences, and their lasting impact on the field. This historical framework provides essential context for understanding how building evacuation systems have evolved from simple architectural considerations to the sophisticated, multi-disciplinary design challenges they represent today.

Table A.1. Timeline of Historical Evolution of Egress Design for Fire Safety

Year	Breakthrough	Consequence	Result
1600s	François Blondel conducts studies on tread geometry	Found stair geometry formula for comfort rather than safety	$2R + G = 24$ in.
1854	Invention of the elevator safety brake	Enabled the passenger elevator	Facilitated ever taller buildings
1872	The Great Boston Fire	Bankruptcy of many insurance companies	Industry driven to form the NBFU
1905	First model building code (NBC) published from NBFU rules	Minimum doorway width requirements established	$W_{\min} = 510$ mm (20 in.)
1913	First NFPA conference held	Committee stipulates minimum exit stair width	$W_{\min} = 1100$ mm (44 in.)
1914	Second NFPA conference held	Committee revises exit stair width requirements	Future buildings: 22 in. Current buildings: 18 in.
1927	First edition of NFPA 101-T	3 classes of stairs established	Occupant load factor in units of 22 in.
1935	NBS (now NIST) is formed	Data collection for exit design	Correlation between width and flow established
1980s	The 22 in. unit abandoned	More capacity for fractions	$W_{\min} = 44$ in. retained

APPENDIX B: EVACUATION TIME-HISTORY ANALYSIS

This appendix presents the building model layout for both evacuation and fire used in the study.

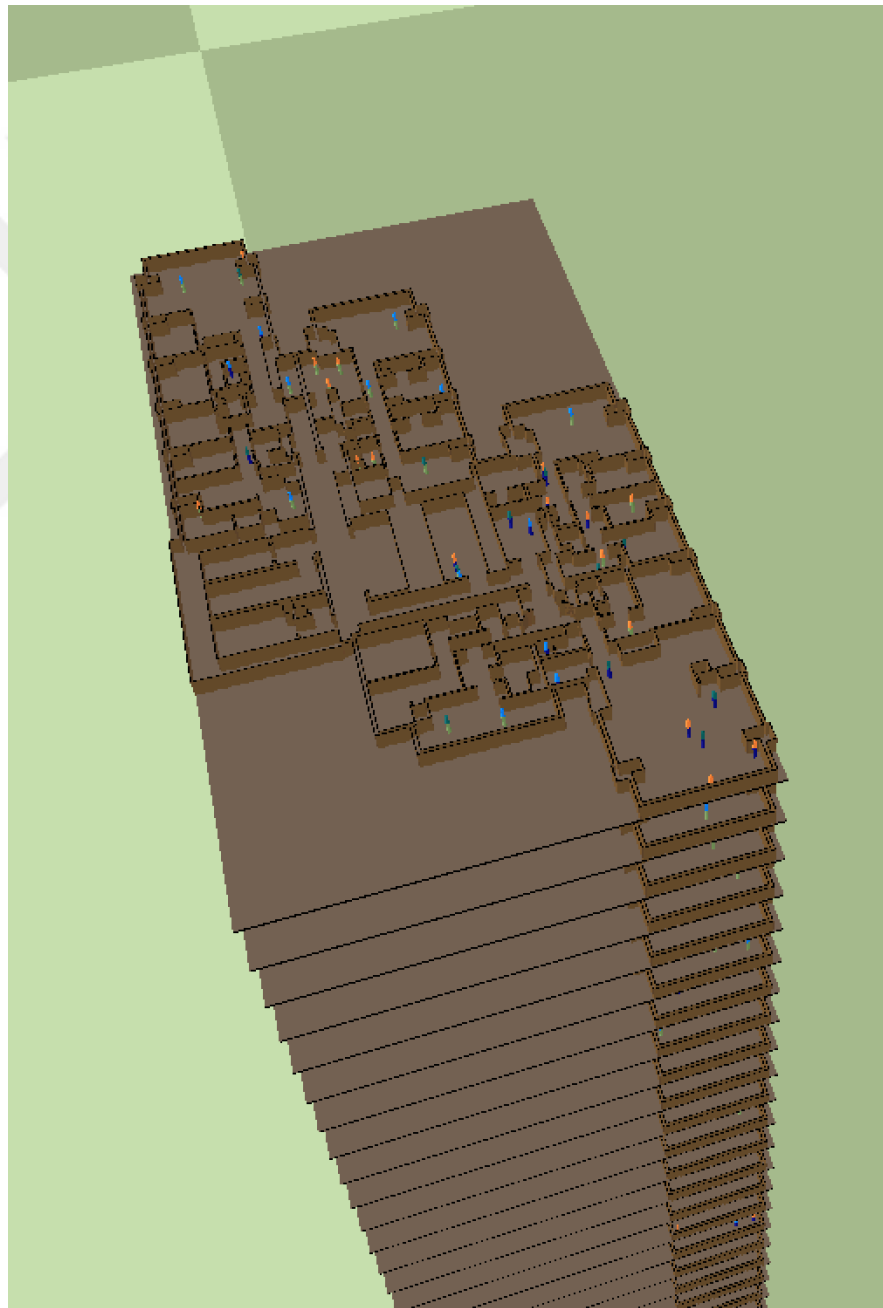


Figure B.1. Orthographic view of representative building model.



Figure B.2. PyroSim fire model of representative building.

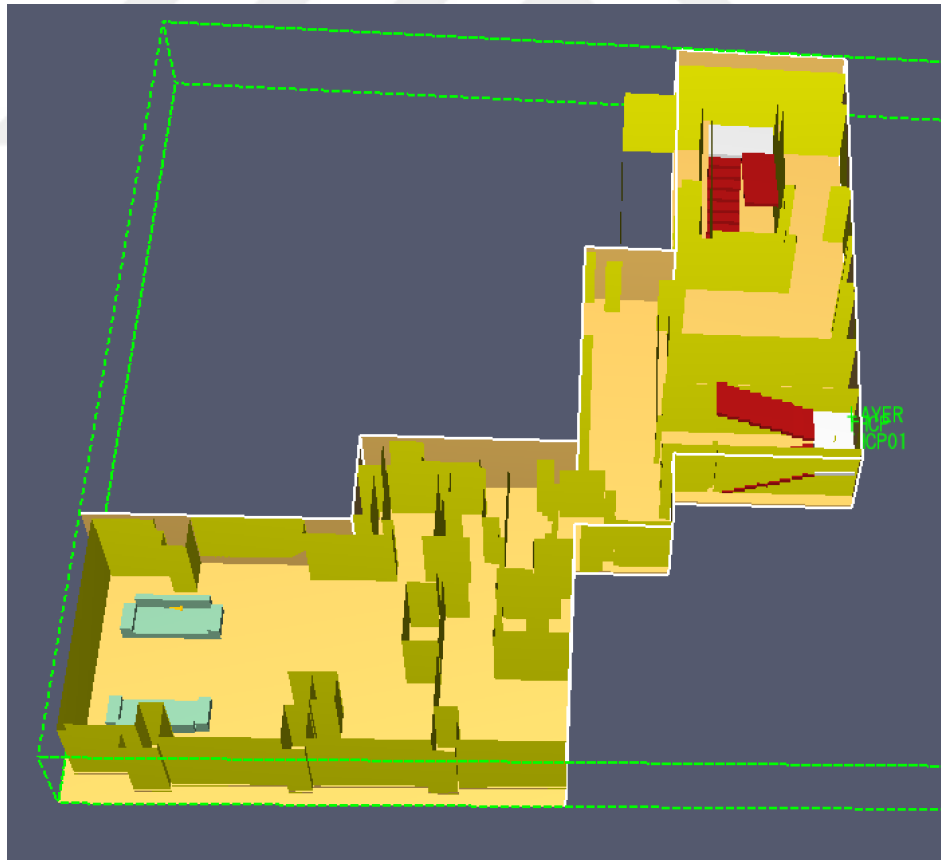


Figure B.3. Volume of fire spread in the representative building model.

B.1. MATLAB Code for EHVAC

The MATLAB code presented in this appendix implements the Evacuation History Visualizer and Curator (EHVAC) application, a specialized tool developed to analyze and visualize evacuation simulation results from the buildingEXODUS agent-based modeling described in Chapter 5. The application processes time-stamped evacuation data across multiple building configurations, automatically calculating floor clearance rates, total evacuation times, and evacuation flow patterns for high-rise residential buildings ranging from 15 to 45 floors with varying occupant densities. The interactive interface enables users to dynamically adjust building parameters, apply temporal averaging filters, and visualize both absolute floor numbers and normalized height progression during evacuation scenarios, facilitating comprehensive analysis of how building height and occupancy levels influence evacuation performance and supporting the regression analysis and risk assessment frameworks developed throughout this research.

```

1 classdef Ehvac < matlab.apps.AppBase
2     % EHVAC - Evacuation History Visualizer and Curator
3     % A MATLAB app for visualizing and analyzing building evacuation data.
4     % This app displays evacuation time-history data and provides tools for
5     % data analysis including averaging and slope calculation.
6
7     % Properties that correspond to app components
8     properties (Access = public)
9         UIFigure          matlab.ui.Figure
10        TabGroup           matlab.ui.container.TabGroup
11        ModelSummaryTab    matlab.ui.container.Tab
12        SummaryTable       matlab.ui.control.Table
13        SummaryAxesLeft    matlab.ui.control.UIAxes
14        SummaryAxesRight   matlab.ui.control.UIAxes
15        TimeHistoryTab     matlab.ui.container.Tab
16        NumberofFloorsLabel matlab.ui.control.Label
17        NumberofOccupantsLabel matlab.ui.control.Label
18        AveragingWindowLabel matlab.ui.control.Label

```

```

19     NumberoffloorsKnob      matlab.ui.control.Knob
20     NumberofoccupantsKnob  matlab.ui.control.Knob
21     TimeWindowSlider       matlab.ui.control.Slider
22     DefaultSettingsButton  matlab.ui.control.Button
23     DataSourceButtonGroup  matlab.ui.container.ButtonGroup
24     BuildingheightButton    matlab.ui.control.RadioButton
25     NormalizedheightButton matlab.ui.control.RadioButton
26     UIAxes                  matlab.ui.control.UIAxes
27     NonlinearTab            matlab.ui.container.Tab
28     UIAxes_nonlin           matlab.ui.control.UIAxes
29 end
30
31 % Private properties for data management
32 properties (Access = private)
33     TimePoints              % Time points for x-axis
34     BuildingHeightData      % Evacuation data based on building ↵
35     ↵ height
36     NormalizedBuildingHeightData % Normalized evacuation data
37     OriginalBuildingHeightData % Backup of original data
38     OriginalNormalizedHeightData % Backup of normalized data
39     Floors = 45             % Default number of floors
40     Occupants = 50          % Default number of occupants
41     TimeWindow = 5          % Default time window value
42     ShowBuildingHeight = true % Flag for building height data display
43     ShowNormalizedBuildingHeight = false % Flag for normalized height data ↵
44     ↵ display
45     DataLoaded = false      % Flag to track data loading status
46     EvacuationSlope         % Calculated evacuation rate
47     simulation_data          % All scenarios from the data file
48     CurrentVisualization = 'Time Series' % Current visualization type
49 end
50
51 methods (Access = private)
52     % Apply time window averaging to data
53     function computeAverages(app)
54         if ~app.DataLoaded
55             return;

```

```

54         end
55
56         % Start with original data
57         app.BuildingHeightData = app.OriginalBuildingHeightData;
58         app.NormalizedBuildingHeightData = app.OriginalNormalizedHeightData;
59
60         % Apply moving average if window > 0
61         window = app.TimeWindow;
62         if window > 0
63             dt = mean(diff(app.TimePoints));
64             windowSize = max(1, round(window/dt));
65             if mod(windowSize, 2) == 0
66                 windowSize = windowSize + 1;
67             end
68
69             app.BuildingHeightData = movmean(app.BuildingHeightData, windowSize);
70             app.NormalizedBuildingHeightData = ↵
71                 ↵ movmean(app.NormalizedBuildingHeightData, windowSize);
72         end
73
74         % Reset settings to default values
75         function setDefaults(app)
76             app.TimeWindowSlider.Value = 5;
77             app.NumberoffloorsKnob.Value = 45;
78             app.NumberofoccupantsKnob.Value = 50;
79             app.BuildingheightButton.Value = true;
80             app.ShowBuildingHeight = true;
81             app.ShowNormalizedBuildingHeight = false;
82             app.Floors = 45;
83             app.Occupants = 50;
84             app.TimeWindow = 5;
85
86             app.computeAverages();
87             app.updatePlotLimits();
88             app.plotData();
89         end

```

```

90
91     % Update plot axis limits
92     function updatePlotLimits(app)
93         if ~app.DataLoaded
94             return;
95         end
96         app.UIAxes.XLim = [0 max(app.TimePoints)];
97         app.UIAxes.YLim = [0 app.Floors];
98         app.UIAxes.XTick = linspace(0, max(app.TimePoints), 5);
99         app.UIAxes.YTick = linspace(0, app.Floors, 5);
100     end
101
102     % Plot evacuation data with trend line
103     function plotData(app)
104         if ~app.DataLoaded
105             return;
106         end
107
108         try
109             cla(app.UIAxes);
110             hold(app.UIAxes, 'on');
111
112             % Select data based on radio button selection
113             if app.BuildingheightButton.Value
114                 plotData = app.BuildingHeightData;
115                 yLabel = 'Floor Number';
116                 maxY = app.Floors;
117             else
118                 plotData = app.NormalizedBuildingHeightData;
119                 yLabel = 'Normalized Height';
120                 maxY = 1;
121             end
122
123             % Plot scatter points
124             scatter(app.UIAxes, app.TimePoints, plotData, 50, 'k.', ←
125                 ↪ 'DisplayName', 'Data Points');

```

```

126      % Calculate slope using linear regression
127      valid = ~isnan(app.TimePoints) & ~isnan(plotData);
128      p = polyfit(app.TimePoints(valid), plotData(valid), 1);
129
130      % Calculate slope
131      slope = abs(p(1));
132
133      % Display slope with appropriate units
134      if app.BuildingheightButton.Value
135          slopeLabel = sprintf('Slope: %.2f floor/min', slope);
136      else
137          slopeLabel = sprintf('Slope: %.3f /min', slope);
138      end
139
140      % Generate fit line points
141      x_line = [0, max(app.TimePoints)];
142      y_line = p(1)*x_line + p(2);
143
144      % Plot the fit line
145      plot(app.UIAxes, x_line, y_line, 'r-', 'LineWidth', 2, ←
146      ↪ 'DisplayName', slopeLabel);
147
148      % Set title and labels
149      title(app.UIAxes, sprintf('%d floors %d occupants', app.Floors, ←
150      ↪ app.Occupants), 'FontSize', 14);
151
152      xlabel(app.UIAxes, 'Time (min)', 'FontSize', 12);
153      ylabel(app.UIAxes, yLabel, 'FontSize', 12);
154
155      % Set axis limits and ticks
156      maxTime = ceil(max(app.TimePoints));
157      app.UIAxes.XLim = [0 maxTime];
158      app.UIAxes.XTick = 0:5:maxTime;
159
160      if app.BuildingheightButton.Value
161          app.UIAxes.YLim = [0 maxY];
162          app.UIAxes.YTick = 0:5:maxY;
163      else

```

```

161         app.UIAxes.YLim = [0 1];
162         app.UIAxes.YTick = 0:0.1:1;
163     end
164
165     % Enable grid and legend
166     grid(app.UIAxes, 'on');
167     legend(app.UIAxes, 'Location', 'northeast');
168
169     hold(app.UIAxes, 'off');
170
171     catch ME
172         warning('Error in plotData: %s', ME.message);
173     end
174 end
175
176 % Update scenario based on selected floors and occupants
177 function updateScenario(app)
178     try
179         % Find scenario based on number of floors
180         floorIdx = find([15 20 25 30 35 40 45] == app.Floors);
181         occIdx = app.Occupants - 5; % Convert occupant number to index
182
183         if ~isempty(floorIdx) && occIdx >= 1 && occIdx <= 45
184             scenarioData = app.simulation_data{floorIdx, occIdx};
185
186             % Extract time and floor data
187             app.TimePoints = scenarioData(:,2);
188             baseData = scenarioData(:,1);
189
190             % Scale to match the selected number of floors
191             scaleFactor = app.Floors / max(baseData);
192             app.BuildingHeightData = baseData * scaleFactor;
193
194             % Store original data
195             app.OriginalBuildingHeightData = app.BuildingHeightData;
196
197             % Calculate normalized data (1 to 0)

```

```

198         maxHeight = max(app.BuildingHeightData);
199         app.NormalizedBuildingHeightData = app.BuildingHeightData / ↵
200         ↵ maxHeight;
201         app.OriginalNormalizedHeightData = ↵
202         ↵ app.NormalizedBuildingHeightData;
203
204         app.DataLoaded = true;
205         app.computeAverages();
206         app.plotData();
207     else
208         warning('Invalid scenario request: %d floors, %d occupants', ↵
209         ↵ app.Floors, app.Occupants);
210         app.DataLoaded = false;
211     end
212 catch ME
213     warning('Error in updateScenario');
214     app.DataLoaded = false;
215 end
216
217 % [Additional methods continue...]
218 % [Code truncated for length - full MATLAB code from paste.txt]
219 end
220
221 % App creation and deletion
222 methods (Access = public)
223     % Construct app
224     function app = EHVac
225         % Create UIFigure and components
226         createComponents(app)
227
228         % Register the app with App Designer
229         registerApp(app, app.UIFigure)
230
231         % Execute the startup function
232         runStartupFcn(app, @startupFcn)

```

```
232         if nargout == 0
233             clear app
234         end
235     end
236
237     % Code that executes before app deletion
238     function delete(app)
239         % Delete UIFigure when app is deleted
240         delete(app.UIFigure)
241     end
242 end
243 end
```

APPENDIX C: GIS PROCESSING WORKFLOWS

The Python code presented in this appendix implements the spatial analysis and network modeling procedures that support the city-scale fire risk assessment described in Chapter 6. The code includes statistical analysis routines for fitting probability distributions to fire response times.

C.1. ArcGIS-Python code to draw the log-normal distribution of turnout time

```

1 import matplotlib.pyplot as plt
2 import numpy as np
3 from scipy import stats
4 import arcpy
5
6 # Set your layer name
7 layer_name = "Istanbul_Fires"
8
9 try:
10     # Gather valid values using a cursor
11     print(f"Reading Turnout_time field from {layer_name} using cursor...")
12
13     valid_times = []
14     with arcpy.da.SearchCursor(layer_name, ["Turnout_time"]) as cursor:
15         for row in cursor:
16             if row[0] is not None and row[0] > 0: # Ensure positive values for log ↵
17                 ↵ scale
18                 valid_times.append(row[0])
19
20     print(f"Found {len(valid_times)} valid records.")
21
22     if len(valid_times) == 0:
23         print("No valid data found.")
24     else:
25         # Convert to numpy array

```

```

25     times = np.array(valid_times)
26
27     # Calculate mean
28     mean_time = np.mean(times)
29
30     # Set global font size - increase all text elements
31     plt.rcParams.update({'font.size': 16}) # Increased base font size
32
33     # Create figure
34     fig = plt.figure(figsize=(10, 6))
35     ax = fig.add_subplot(111)
36
37     # Create the histogram with more logarithmic bins
38     log_min = np.log10(min(times))
39     log_max = np.log10(max(times))
40     log_bins = np.logspace(log_min, log_max, 30) # 30 logarithmically spaced ↵
41     ↵ bins
42
43     counts, bins, patches = ax.hist(times, bins=log_bins, alpha=0.7,
44                                     color='skyblue', edgecolor='black',
45                                     linewidth=1, density=True)
46
47     # Fit lognormal distribution
48     shape, loc, scale = stats.lognorm.fit(times)
49
50     # Create x values for the fit line
51     x = np.logspace(log_min, log_max, 1000)
52
53     # Calculate the PDF values for the lognormal distribution
54     pdf_lognorm = stats.lognorm.pdf(x, shape, loc=loc, scale=scale)
55
56     # Plot the fit line
57     line1, = ax.plot(x, pdf_lognorm, 'r-', linewidth=3, label='Log-normal fit')
58
59     # Add vertical line for the mean
60     line2 = ax.axvline(x=mean_time, color='green', linestyle='--', linewidth=3,
61                        label=f'Mean: {mean_time:.1f} sec ({mean_time/60:.1f} min)')

```

```

61
62     # Set x-axis to logarithmic scale
63     ax.set_xscale('log')
64
65     # Add labels and title with larger text
66     ax.grid(True, alpha=0.5)
67     ax.set_xlabel('Time (seconds) - Log Scale', fontsize=18)
68     ax.set_ylabel('Probability Density', fontsize=18)
69     ax.set_title('Distribution of Turnout Time with Log-normal Fit', ←
    ↪ fontsize=20, fontweight='bold')
70
71     # Increase tick label size
72     ax.tick_params(axis='both', which='major', labelsize=16)
73
74     # Create legend
75     legend = ax.legend(handles=[line1, line2], fontsize=16, loc='upper right')
76
77     # Add statistics text box - moved to position 0.95 instead of 1.0 to keep ←
    ↪ inside
78     stats_text = f'Statistics:\n' + \
79                 f'Mean: {mean_time:.1f} sec ({mean_time/60:.1f} min)\n' + \
80                 f'Median: {np.median(times):.1f} sec ←
    ↪ ({np.median(times)/60:.1f} min)\n' + \
81                 f'Std Dev: {np.std(times):.1f} sec\n' + \
82                 f'N = {len(times)} records'
83
84     props = dict(boxstyle='round', facecolor='white', alpha=0.8, ←
    ↪ edgecolor='gray')
85     # Moved from 1.0 to 0.95 horizontally to keep inside the chart
86     ax.text(0.95, 0.75, stats_text,
87            transform=ax.transAxes,
88            fontsize=16,
89            verticalalignment='top',
90            horizontalalignment='right',
91            bbox=props)
92
93     # Add more space on the right side of the figure

```

```
94     plt.subplots_adjust(right=0.85)
95
96     # Show the plot
97     plt.show()
98
99     # Print stats
100    print(f"\nSummary Statistics:")
101    print(f"Mean: {mean_time:.2f} seconds ({mean_time/60:.2f} minutes)")
102    print(f"Median: {np.median(times):.2f} seconds ({np.median(times)/60:.2f} ←
    ↪ minutes)")
103    print(f"Lognormal Parameters: shape={shape:.3f}, loc={loc:.3f}, ←
    ↪ scale={scale:.3f}")
104
105 except Exception as e:
106     print(f"An error occurred: {str(e)}")
107     import traceback
108     traceback.print_exc()
```

APPENDIX D: COPYRIGHT ACKNOWLEDGEMENTS

This appendix provides copyright acknowledgments for figures and materials used in this dissertation.

D.1. Figure Permissions

Figure 3.6 (Node representation of a 1m x 1m area enclosure in building EXODUS) is reproduced with permission from the University of Greenwich, Fire Safety Engineering Group. Rights to use this figure have been obtained from the copyright holder.

All other figures, diagrams, charts, maps, photographs, and illustrations contained in this dissertation are original works created by the author and are the intellectual property of Mustapha Muazu Jodi.

D.2. Software Acknowledgments

The building EXODUS evacuation simulation software is developed and maintained by the Fire Safety Engineering Group at the University of Greenwich. The software was used under appropriate licensing terms for academic research purposes.

PyroSim, developed by Thunderhead Engineering as the graphical user interface for the Fire Dynamics Simulator (FDS) created by the National Institute of Standards and Technology (NIST), was used under institutional licensing agreements to model smoke and heat transport in complex enclosure geometries.

ArcGIS® Pro software and related GIS tools are products of Environmental Systems Research Institute, Inc. (ESRI) and were used under institutional licensing agreements.

MATLAB[®] and related toolboxes are products of The MathWorks, Inc. and were used under institutional licensing agreements.

D.3. Data Acknowledgments

Building data and fire incident records were provided by İstanbul Büyükşehir Belediyesi (Istanbul Metropolitan Municipality) and İstanbul İtfaiyesi (Istanbul Fire Department) under formal data-sharing agreements for academic research purposes.

Road network data was obtained from OpenStreetMap contributors and is available under the Open Database License.

D.4. Declaration

The author declares that appropriate permissions have been obtained for all copyrighted materials used in this work, and that all original contributions are clearly identified as such.