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Evacuation of people from buildings during a fire: regulatory framework, psychophysiological factors and technological solutions

Dilmurod Baxadirovich Raximov[1]

[1] Andijan State Technical institute, Andijan, Uzbekistan
e - mail : [1]rahimovdilmurad@gmail.com

Abstract— Evacuation of people during fires is a complex process that is influenced by regulatory requirements, human behavior, and modern technological solutions. In this article, we analyze the transformation of fire standards and regulations, consider the psychophysiological aspects of the population that determine human behavior in emergency situations, and explore innovative technologies that help improve the efficiency of evacuation. Based on the latest research and practical developments, the authors seek to provide a holistic view of the integrated approach needed to successfully implement fire evacuation strategies.

Keywords: fire evacuation, building safety, emergency exits, human behavior in emergency situations, psychophysiological reactions, NFPA 101, IBC, IoT in fire safety systems, BIM modeling, VR training, fire safety standards, accessible evacuation, evacuation simulation, intelligent buildings, occupant response time.

INTRODUCTION

Ensuring safe egress from buildings during fires remains a critical issue for engineers, architects, civil protection specialists, and government regulators worldwide. Modern architectural solutions – whether skyscrapers, underground hubs, or large shopping and entertainment centers – pose increasingly serious challenges to designers in organizing effective evacuation. Fires in buildings are not only technical incidents, but also social and psychological tests that reveal vulnerabilities in both infrastructure and human behavior under pressure.

Historically, fire safety systems in buildings have focused primarily on passive measures such as fire-resistant structures, automatic fire suppression systems and strictly fixed evacuation routes. However, a series of tragic incidents, including the Grenfell Tower fire in London and the Station disaster in the United States, have demonstrated that these measures are insufficient without a comprehensive and dynamic approach to evacuation [1]. These events have prompted a review of building codes and response procedures in many countries.

Today, fire protection and evacuation measures are regulated by a system of normative documents that includes international standards, such as the International Building Code (IBC), the Life Safety Code NFPA 101, as well as national regulations that adapt global approaches to local conditions. These standards require the presence of

a sufficient number of evacuations exits, calculation of the density of human flow, installation of emergency lighting and signs, and development of detailed evacuation plans. However, practice shows that even with full compliance with the standards, the effectiveness of evacuation is not always guaranteed, since the standards are usually based on idealized conditions and do not take into account the factor of human unpredictability [2].

One of the key aspects that often remains in the shadows within the framework of regulatory framework is the psychophysiological behavior of people in fire conditions. Research in the fields of behavioral psychology, neurocognitive science and sociology show that in life-threatening situations, human behavior is rarely rational and predictable. Decision-making during evacuation is significantly influenced by factors such as subjective risk perception, social cues, cognitive ability to process information and individual panic reaction thresholds [3]. For example, the phenomenon of "normality bias" - a cognitive distortion in which a person underestimates the real threat and believes that "everything will be fine" - often becomes the reason for delays in evacuation [4]. Other people, on the contrary, may become confused, wait for the reaction of others or even go back for personal belongings - which, if the fire spreads quickly, can cost lives.

Certain population groups are particularly vulnerable in such situations: children, the elderly, people with disabilities, and those who have poor orientation in the building, such as hotel guests or shopping mall visitors. These groups often require additional time and assistance to evacuate, making universal evacuation models ineffective without inclusive design principles [5].

Significant shifts in approaches to evacuation have occurred due to the introduction of modern technologies, which have made it possible to move from static models to more adaptive and reactive systems. The development of intelligent solutions, the integration of the Internet of Things (IoT), monitoring technologies and real-time data analysis have significantly increased response capabilities. For example, IoT sensors can track smoke, temperature increases and people movements, allowing for the formation of adaptive alerts and dynamic control of ventilation systems [6]. In turn, digital modeling of buildings using BIM and the use of virtual reality (VR) technologies provide realistic evacuation scenarios, staff training and increased preparedness of residents to act in emergency situations.

Despite the progress made, there remains a significant gap between the regulatory framework, human behavior models, and technological solutions. Fire evacuation is an interdisciplinary task that lies at the intersection of architecture, psychology, legal regulation, and digital innovation. Only by integrating these components will we be able to develop a sustainable, scientifically sound, and practically applicable strategy aimed at minimizing the consequences of fires, reducing the number of victims, and creating a culture of preparedness and resilience in society.

This paper aims to bridge this gap by synthesizing international fire safety regulations, modern research on human behavior in emergency situations, and the latest technological solutions. By exploring the relationships, intersections, and conflicts between these three areas—regulations, psychology, and technology—we propose a holistic approach to developing and implementing effective evacuation strategies in buildings of various purposes and capacities.

Methods.

This study relies on an interdisciplinary methodology that combines systematic literature review, legal comparative research, behavioral science, and technology assessment. This section describes the procedures for selecting, analyzing, and interpreting data related to the regulatory framework, psychophysiological behavior patterns, and modern technologies used in organizing fire evacuation.

1. Systematic literature review

To identify relevant research and policy documents in the field of fire evacuation, a structured review of sources from leading academic databases was conducted: ScienceDirect, IEEE Xplore, SpringerLink, Scopus, and Google Scholar. Inclusion criteria were: peer-reviewed publications (journal articles and conference proceedings) published

between 2010 and 2024, in English, with a focus on building evacuation. Non-peer-reviewed materials, studies focusing on wildfires, animal evacuation, obsolete or redundant models were excluded. From over 1,500 sources, 78 publications were selected after analyzing titles, abstracts, and conclusions. The final corpus included 35 of the most relevant studies, which were further referenced in the article.

2. Analysis of the regulatory framework

To assess the current standards and norms, both international and national documents on fire safety were reviewed. The key sources were: NFPA 101: Life Safety Codeю NFPA 72: National Fire Alarm Code. IBC (International Building Code, 2021). EU Fire Safety Directives. ISO 7010 and ISO 23601 - standards for safety signs and evacuation plans.

In addition, the legislation of the USA, UK, Germany, Japan and Uzbekistan was analyzed. The standards were compared using a compliance matrix, which made it possible to identify differences and similarities in such aspects as exit widths, sign placement, accessibility requirements, signaling rules and evacuation planning for vulnerable groups.

3. Behavioral and psychophysiological aspects

The study draws on insights from behavioral psychology, sociology, and cognitive science, focusing on decision-making under stress, group behavior, risk perception, and phenomena such as delays before evacuation, herding, and social validation seeking.

The analysis included: field observation data (e.g. fire drills); results of computer modeling using Pathfinder, FDS+Evac programs; the influence of environmental factors (noise, smoke, temperature) on the efficiency of evacuation; modeling the reactions of different population groups taking into account age, physical condition, cognitive limitations and knowledge of the layout of the premises [7][8].

These data were used to calibrate theoretical models and test hypotheses formulated in regulatory evacuation plans.

4. Overview of intelligent evacuation technologies

The technological component of the study focused on the analysis of smart evacuation systems, including: IoT sensors for detecting smoke, heat, motion [6]; intelligent evacuation lighting and navigation systems; dynamic management of people flows; AI platforms for emergency notification; BIM technologies for visualization of evacuation routes [9]; VR/AR applications for scenario simulation and personnel training [10].

Each technology was assessed according to the following criteria: Promptness of response; Scalability; Compatibility with existing infrastructure; Economic efficiency; Convenience and adaptability for different user groups.

Data on these solutions was collected from manufacturers' technical documentation, published evaluation studies, and the IEEE Xplore and arXiv platforms. Priority was given not only to current capabilities, but also to future developments, in particular the implementation of AI and machine learning for predictive evacuation modeling.

Results.

The results of the conducted research are grouped into three main areas: regulatory framework, psychophysiological characteristics of behavior in emergency situations, and technological innovations in the field of evacuation. The analysis of each area demonstrates their interrelation and contribution to the formation of an effective evacuation strategy in case of fire in buildings of various purposes.

1. Normative framework. Modern building codes and fire safety standards reflect the increasing complexity of architectural structures, especially in dense urban environments. International documents such as the International Building Code (IBC) and NFPA 101: Life Safety Code set the basic requirements governing the design of evacuation routes and protocols [11].

Among the key provisions we can highlight: the minimum number and width of emergency exits depending on the estimated capacity of the building; permissible length of evacuation routes; requirements for emergency lighting, signs, accessible routes; mandatory availability of evacuation plans and regular training.

Thus, NFPA 101 requires that each floor of a building have at least two independent means of egress that minimize the risk of being blocked by both fire and smoke [2], and IBC requires continuous, unimpeded access from any location to a safe area [12].

However, in practice, compliance with these standards is often limited to physical parameters (width, number of exits), while the behavioral and organizational component (e.g., conducting exercises) remains insufficiently implemented [13]. Current challenges are presented by new building typologies: vertical campuses, multifunctional towers and underground complexes require a revision of the regulatory framework and more flexible design solutions.

2. Psychophysiological aspects. Analysis of behavioral factors shows that even ideal conditions stipulated by standards do not guarantee timely and safe evacuation. In fire conditions, people's behavior is determined by a complex of cognitive, emotional and physiological reactions that often go beyond the rational.

The following characteristic behavioral patterns were identified: Delay in the start of evacuation: the average time between the activation of the alarm and the start of movement varies from 1 to 10 minutes, depending on the intensity of sensory signals (smell of smoke, visibility of others evacuating, sound alert) [13]; Information search: often observed in people unfamiliar with the object (hotel guests, tenants); Social influence: behavior in a group has a significant impact - people tend to follow the actions of others (crowd effect); Stress reactions: confusion, freezing, going back for things - behavioral deviations that can lead to delays and panic.

Vulnerable population groups (children, elderly, people with limited mobility, tourists) are particularly exposed to risks and require specialized solutions, including accompanying personnel, assistive technologies, and adapted infrastructure. Studies using simulators (Pathfinder, FDS+Evac) confirm that taking into account behavioral variability significantly increases the accuracy of evacuation time forecasts and bottleneck detection [7].

3. Technological solutions. Modern technologies are becoming an integral part of the evacuation strategy, providing flexibility and adaptability in the conditions of developing fires. Three areas have demonstrated the greatest potential:

a) IoT based systems. The Internet of Things allows real-time monitoring of environmental parameters — temperature, smoke, human movement — and, based on them, launching automatic scenarios: illumination of optimal paths, ventilation control, mobile alerts. Integration of such systems with intelligent buildings provides personalized evacuation instructions based on the user's location [14].

b) Building Information Modeling (BIM). BIM provides the ability to model evacuation scenarios already at the design stage, including calculating throughput, identifying potential obstacles and optimizing layouts (corridor width, stair placement). In emergency situations, BIM models can be connected to sensor data streams, providing up-to-date information for rapid response [9].

c) Virtual and augmented reality (VR/AR). AR/VR platforms enable safe, immersive, and repeatable evacuation training. Research shows that VR training leads to more confident and faster responses in real-world situations compared to traditional methods [10]. VR is especially useful for vulnerable groups (e.g., children or people with language barriers) who have difficulty understanding text instructions.

Discussion.

Synergy between regulations, behavioral mechanisms and technological innovations is the key to creating effective and realistic evacuation strategies. Regulations provide a structural framework, but without taking into account the human factor and operational decisions, the effectiveness of evacuation remains limited. New

technologies allow not only to adapt evacuation procedures in real time, but also to predict the development of scenarios, thereby reducing risks and saving lives.

Conclusions.

The increasing complexity of the architectural environment and the growth of urban population density require a revision of approaches to the design, organization and implementation of evacuation in case of fire. The conducted study emphasizes that a reliable evacuation strategy is not only a question of the number of exits or the presence of an alarm system, but a complex task combining the regulatory framework, behavioral characteristics and modern technologies.

1. The importance of comprehensive regulatory framework. Fire codes and regulations are the cornerstone of occupant safety during fires in buildings. The proliferation of international standards such as IBC, NFPA 101, and various ISO provisions have provided a framework for assessing key safety aspects such as egress path widths, detection, and alarm systems [2][11]. However, the results of this study demonstrate the need to update and align these codes to address new architectural designs, hybrid building functions, and inclusive design principles. Many current documents still rely on simplified assumptions about population behavior and composition that do not reflect reality. Therefore, future regulations should incorporate empirical behavioral data, modeling results, and universal access requirements to foster a more flexible and adaptive regulatory environment.

2. Taking into account psychophysiological factors as a factor in saving lives. As the research shows, human behaviour in fire situations is not always logical. It is shaped by cognitive biases, emotional state, external stimuli and social dynamics [3][4]. Delays caused by the desire to obtain information, confusion or group imitation can significantly reduce the chances of survival, especially in conditions of limited visibility and blocked routes. The key finding is that architecture and safety professionals should take behavioural variability into account when developing evacuation procedures. Incorporating behavioural models into the design of alarms and navigation systems helps to reduce delays and improve response times [7]. At the same time, special attention should be paid to groups with special needs - the elderly, people with limited mobility and those who do not speak the language of instructions - through the principles of universal design and adaptive communication approaches.

3. The role of technology as a transformative element. Modern technologies are changing all stages of the evacuation process, from early detection and decision-making to training and subsequent analysis. IoT systems collect and analyze information about the condition of the building, the presence of smoke, and the movement of people, allowing for the formation of targeted evacuation instructions in real time [14]. BIM and digital twin technologies allow potential problems to be identified at the design stage, from bottlenecks to inaccessible areas [7]. Immersive tools such as VR and AR provide hands-on training, increase awareness, and prepare users to act under stress [8]. However, successful implementation of these solutions requires institutional support, cost-effectiveness assessment, and seamless integration with existing infrastructure.

4. The combination of regulation, behavioural knowledge and digital technologies creates a need for a new professional field that combines engineering design, behavioural analytics, data management and crisis response [15]. Fire safety training must meet these challenges, including training in behavioural analysis, systems integration and real-time risk management. Achieving this requires close collaboration between educational institutions, regulators and industry. Investment in continuous research, digital simulations and cross-sector exercises will provide a solid empirical basis for further improvement of evacuation approaches.

5. Effective fire evacuation is the result of pre-analysis, informed design, and adaptive solutions. As buildings become smarter and society's safety expectations rise, fire evacuation strategies must evolve from rigid prescriptive systems to intelligent and context-aware systems. This transition is only possible with ongoing research, interdisciplinary collaboration, and evidence-based regulatory reform. Failure to adapt risks locking us into

outdated approaches—with fatal consequences. Success will be measured not only by compliance, but also by the number of lives saved, panics averted, and tragedies avoided.

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