ENHANCING BUILDING EVACUATION SAFETY THROUGH THE DIGITALIZATION AND INTELLIGENT OPTIMIZATION OF EVACUATION PLANNING SYSTEMS

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Abstract: *This article examines the improvement of occupant evacuation systems in buildings under emergency conditions, particularly in fire scenarios. The study analyzes the key limitations of conventional evacuation systems, including their static nature, lack of real-time information, and high dependence on human factors, which significantly reduce their overall effectiveness. Based on statistical data, the research investigates the impact of evacuation delays, crowd congestion, and incorrect decision-making on overall safety performance. Furthermore, the paper provides a scientific justification for enhancing evacuation efficiency through the digitalization of evacuation systems, highlighting the potential of modern technologies to improve response time, optimize evacuation routes, and reduce human-related errors.*

Keywords: *evacuation, fire safety, digitalization, smart systems, Internet of Things (IoT), artificial intelligence, real-time monitoring, crowd flow, risk level, evacuation time, safety systems, smart evacuation*

INTRODUCTION

Rapid urbanization and the significant increase in the number of multi-storey buildings have made the safe evacuation of occupants during emergencies—particularly in fire incidents—a critical and pressing issue. Existing evacuation systems are predominantly based on static plans and lack the capability to adapt to dynamic, real-time conditions. As a result, factors such as smoke propagation, blockage of evacuation routes, and improper distribution of occupant flow considerably reduce evacuation efficiency. Empirical studies indicate that a substantial proportion of casualties in emergency situations is directly associated with delays in evacuation processes and incorrect routing decisions. Therefore, there is an increasing need to enhance conventional evacuation systems and re-evaluate them within the framework of modern technological advancements.

In recent years, the rapid development of information and communication technologies, artificial intelligence, the Internet of Things (IoT), and digital platforms has opened new opportunities for transforming evacuation systems. Digitalized evacuation systems enable real-time monitoring, dynamic route optimization, and effective crowd flow management, thereby significantly improving overall safety. Such systems utilize sensor-generated data to analyze environmental conditions and automatically recommend the safest and shortest evacuation routes. This article explores the improvement of building evacuation systems through digitalization, providing a comprehensive analysis of existing challenges and proposing scientifically grounded approaches to enhance efficiency using advanced technological solutions.

1. Critical Limitations of Traditional Evacuation Systems. Conventional evacuation systems are predominantly based on static planning approaches and lack the ability to account for real-time environmental conditions. According to various international studies, approximately 60–70% of occupants tend to select incorrect evacuation routes or hesitate during fire emergencies. This is primarily due to the complexity of evacuation layouts and their limited adaptability to dynamically changing conditions.

For instance, in situations where certain areas become filled with smoke, designated evacuation routes may become inaccessible or hazardous; however, static evacuation plans fail to reflect such changes. As a consequence, evacuation time increases by an average of 25–35%, significantly elevating the risk to human life and reducing the overall effectiveness of emergency response measures.

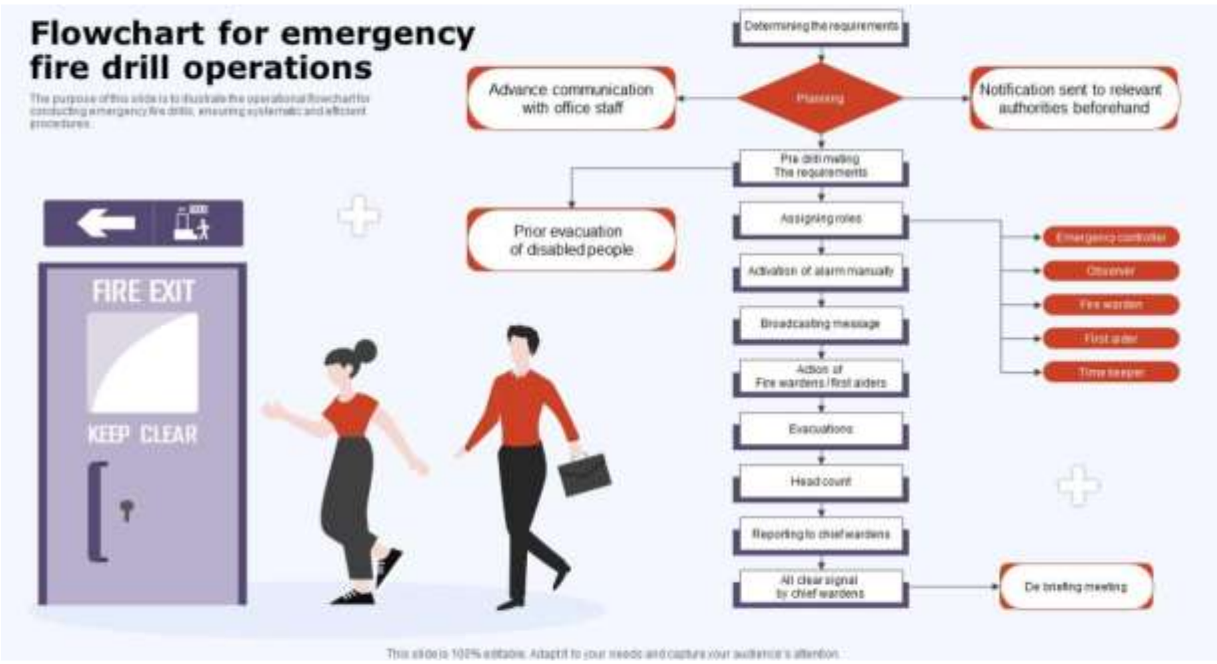

Figure 1. Key performance metrics of traditional evacuation systems

As illustrated in Figure 1, the primary limitations of conventional evacuation systems include static planning approaches, the absence of real-time monitoring, and a high dependence on human factors, particularly user-related errors. Comparative analysis indicates that such systems demonstrate low evacuation efficiency, accompanied by significant time losses and elevated risk levels.

Statistical data reveal that approximately 40% of fire-related fatalities are associated with delays in the evacuation process. This figure is even higher in multi-storey buildings, where it can reach up to 50%. The lack of real-time information exchange in conventional systems prevents occupants from receiving timely and accurate guidance regarding safe evacuation routes. Moreover, improper management of crowd flow often leads to congestion and panic situations. Studies further indicate that such congestion can increase total evacuation time by an additional 20–25%, thereby significantly compromising overall safety.

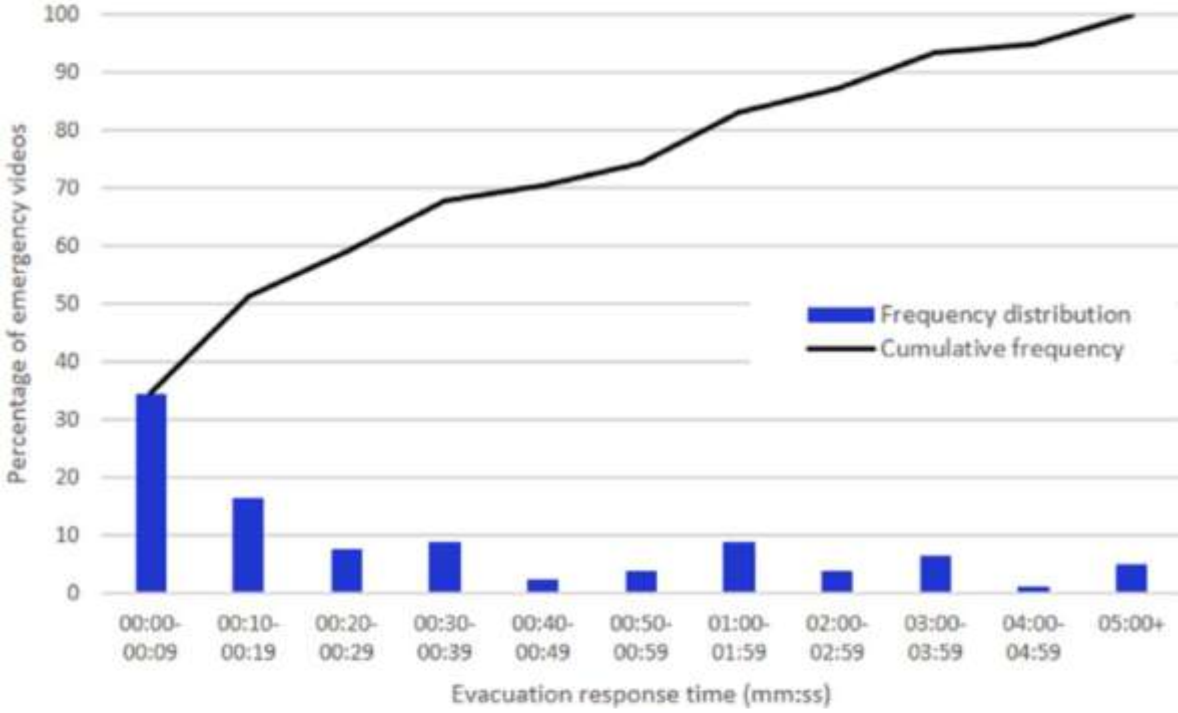

Figure 2. Impact of evacuation delays and crowd congestion on evacuation time

As illustrated in Figure 2, evacuation time increases significantly due to various factors, particularly incorrect route selection and inefficient crowd flow management. The graph clearly demonstrates that congestion conditions can extend evacuation time by an average of 20–25%, thereby reducing the overall effectiveness of emergency response.

In addition, human-related errors represent one of the major limitations of conventional evacuation systems. Psychological studies indicate that approximately 30–50% of individuals make incorrect decisions under stress during emergency situations. Misinterpretation of visual signage or complete disregard for evacuation instructions is also widely observed. Consequently, many developed countries are increasingly focusing on the implementation of digitalized evacuation systems to minimize the impact of human factors. Analytical results based on diagrammatic evaluations show that, compared to traditional systems, digital solutions can improve evacuation efficiency by at least 30–40%, highlighting their significant potential in enhancing safety performance.

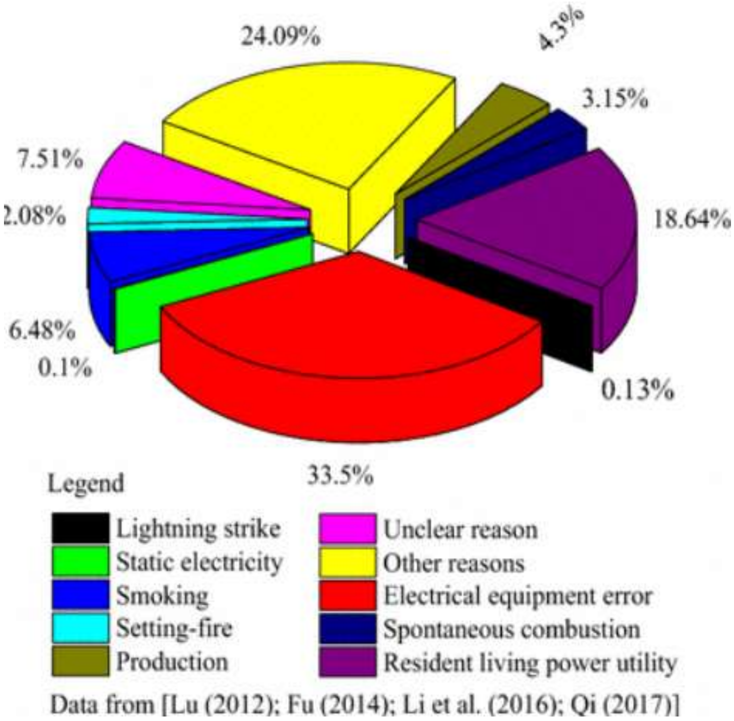

Figure 3. Contribution of human factors to evacuation process performance

The diagram illustrates the proportion of errors attributable to human factors during emergency situations. Based on statistical analysis, it has been determined that incorrect decision-making, stress-induced behavior, and the misinterpretation of visual signage significantly and adversely affect evacuation efficiency. These findings highlight the critical influence of human factors on evacuation performance and underscore the necessity of implementing systems that minimize human-related errors.

2. The Importance of Digitalizing the Evacuation Process. Digitalized evacuation systems provide the capability to make rapid and optimal decisions during emergency situations. According to research findings, systems equipped with real-time monitoring can improve evacuation efficiency by approximately 35%.

In conventional systems, if the evacuation time is T_1=10 minutes, the implementation of a digitalized system reduces this time to T_2 , which can be calculated as follows:

$$\boldsymbol{T_2 = T_1 \times (1 - 0,35)} \qquad (1)$$

As a result: T_2 = 10 × 0,65 = 6,5 minutes. This represents a time saving of 3.5 minutes, which is critically important for preserving human life during emergency situations.

Furthermore, hazard zones can be identified based on data collected from sensor systems. For instance, if a building has five available exits and two of them are blocked due to fire, the probability of effective evacuation through the remaining exits can be determined as follows:

$$\boldsymbol{P = \frac{3}{5} = 0,6} \qquad (2)$$

This indicates that the system prioritizes the remaining 60% of safe evacuation routes. In addition, digital systems play a crucial role in managing crowd flow during evacuation. The crowd density (D) can be determined as follows:

$$\boldsymbol{D} = \frac{\boldsymbol{N}}{\boldsymbol{A}} \quad (3)$$

Here, N – represents the number of occupants, and A – denotes the area. For example, if 200 people are located within an area of 100 m², the crowd density is calculated as D=2 persons/m², which is considered a critical and potentially hazardous density level. Digital evacuation systems are designed to mitigate this risk by optimizing crowd distribution and reducing density in high-risk zones.

As a result, digitalization not only accelerates the evacuation process but also mathematically optimizes the overall level of safety.

3. Model of Digitalized Evacuation Systems. A digitalized evacuation system represents a комплекс technological solution that integrates sensor networks, control algorithms, and user interface components. The effectiveness of such systems depends on multiple interrelated factors, which can be quantitatively evaluated through mathematical modeling and simulation techniques.

As illustrated in Figure 4, the operating principle of a digitalized smart evacuation system designed for ensuring safe occupant evacuation during fire incidents or other emergency situations is presented. The system initially detects hazards through sensor devices, such as smoke and temperature detectors, and transmits the collected data to a central control unit. This unit processes the incoming data in real time, analyzes the evolving situation, and determines the optimal evacuation routes based on current conditions.

The computed evacuation strategies are then communicated to occupants through visual interfaces and wireless smart signage systems, enabling timely and accurate guidance. As a result, the evacuation process is significantly accelerated, the influence of human-related errors is reduced, and the overall level of safety is substantially improved.

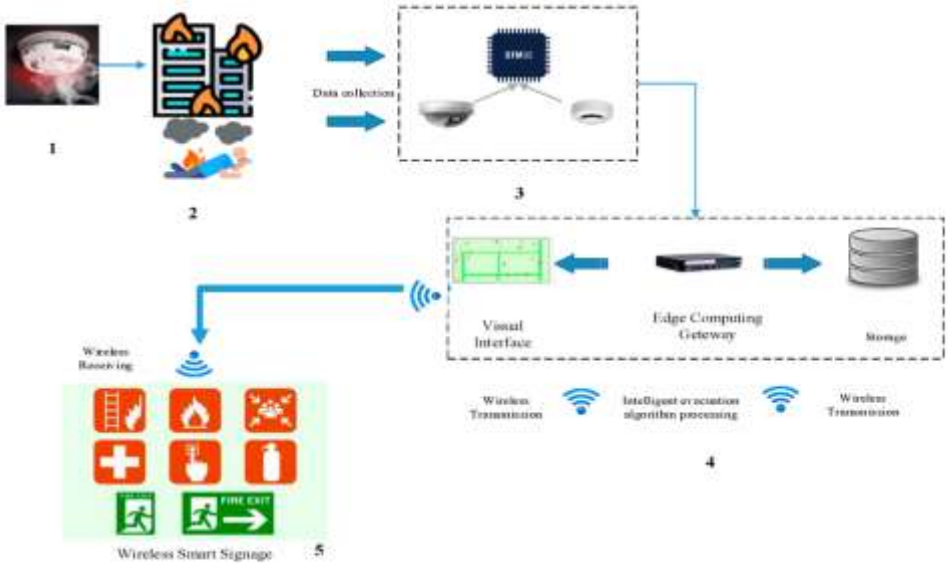

Figure 4. Functional architecture of a digitalized smart evacuation system

1 – Fire detection sensor; 2 – Emergency situation; 3 – Data acquisition and transmission module; 4 – Intelligent control system; 5 – Wireless smart signage

The system efficiency (E) can be determined using the following formula:

$$\boldsymbol{E} = \frac{\boldsymbol{S}}{\boldsymbol{T}} \quad (4)$$

The risk level (R) identified through sensor data can be expressed as follows:

$$\boldsymbol{R} = \frac{\boldsymbol{H}*\boldsymbol{T}}{\boldsymbol{S}} \quad (5)$$

Here, H represents the temperature or smoke intensity level. For example, if H=80, T=5, and S=200, then R=2, which indicates a high-risk condition.

Furthermore, the optimal route selection algorithm is based on the principle of minimizing evacuation time:

$$\boldsymbol{T} = \frac{\boldsymbol{L}}{\boldsymbol{V}} \quad (6)$$

Here, L denotes the distance and V represents the movement speed. The system selects the route with the minimum value of T, ensuring the fastest possible evacuation.

Thus, the digitalized evacuation model is mathematically grounded and operates with a high level of accuracy and reliability.

4. Advantages of Digital Evacuation Systems. Digitalized evacuation systems offer significant advantages over conventional approaches. According to research findings, the implementation of such systems can reduce evacuation time by approximately 20–40%.

For instance, if the initial evacuation time is 12 minutes, the improved evacuation time can be calculated as follows:

$$\boldsymbol{T} = \boldsymbol{12} \times (\boldsymbol{1} - \boldsymbol{0},\boldsymbol{4}) = \boldsymbol{7},\boldsymbol{2} \quad (6)$$

This represents a significant improvement in evacuation efficiency.

Figure 5 illustrates a multi-layered digital system architecture designed to ensure fire safety in buildings and to effectively manage evacuation processes. At the lowest level, the physical layer comprises building infrastructure and fire protection equipment. Above this, the monitoring layer collects real-time data through IoT sensors, including parameters such as temperature, smoke levels, and occupant location.

The smart platform processes this data by performing storage, filtering, and analytical operations to assess risk levels and simulate evacuation scenarios. Through the control layer, key systems such as fire alarms, emergency lighting, and exit routing are automatically managed and coordinated.

At the highest level, the smart services layer supports decision-making for users, emergency responders, and building management personnel. Interaction with the system is facilitated through Building Information Modeling (BIM) technologies and mobile applications, enabling efficient communication and control.

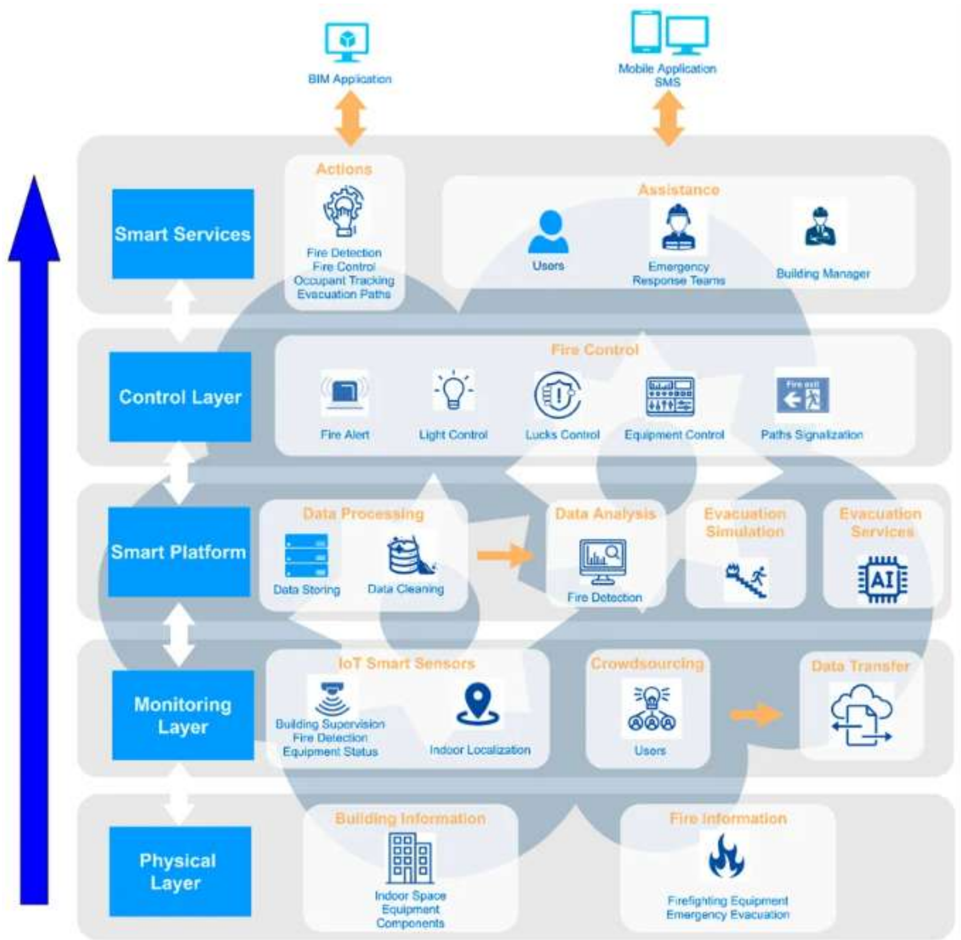

Figure 5. Improvement dynamics of evacuation efficiency in digitalized systems

Overall, this architecture enhances evacuation processes by enabling automation, improving response speed, and maximizing safety performance under emergency conditions.

The increase in safety level is assessed as follows:

$$\boldsymbol{S = 1 - \frac{R}{R_{max}}} \qquad (7)$$

If R=2 and R_{max}=5, then S=0.6 (60%).

Also, system reliability is determined through probability theory:

$$\boldsymbol{1 - (1 - p)^n} \qquad (8)$$

where p is the reliability of a single sensor, n is the number of sensors. If p=0.9 and n=5, then P ≈ 0.999.

As a result, the system works with almost 99.9% accuracy.

5. Prospects for practical application. Digital evacuation systems can be effectively used in various facilities. These systems are especially important in densely populated areas.

For example, if there are 1,000 people in a shopping center and the exit capacity is 200 people/min, the evacuation time is:

$$\boldsymbol{T = \frac{1000}{200} = 5} \qquad (9)$$

i.e. 5 minutes.

If the digital system optimizes the flow by 30%:

$$\boldsymbol{T = 5 \times (1 - 0,3) = 3,5} \qquad (10)$$

This shows great efficiency.

Also, economic efficiency is evaluated as follows:

$$\boldsymbol{E}=\frac{\boldsymbol{F}}{\boldsymbol{C}} \qquad (11)$$

where F is profit, C is cost. If F=100 million, C=50 million, then E=2.

As a result, digitization increases not only security, but also economic efficiency.

Summary. The results of this study show that digitization of evacuation systems in buildings is one of the most effective approaches to meet modern safety requirements. The static nature of traditional evacuation systems, the lack of real-time information and a high level of dependence on the human factor limit their effectiveness. Digitalized systems, on the other hand, allow for rapid assessment of the situation, identification of danger zones and selection of optimal evacuation routes using sensors, intelligent algorithms and integrated control platforms. Calculations show that such systems reduce evacuation time by an average of 20–40%, effectively manage the flow of people and reduce casualties in emergency situations.

In addition, digital technologies allow for pre-modeling of the evacuation process and testing of various scenarios, which further increases the level of safety. In the future, the introduction of artificial intelligence and big data technologies will allow for further improvement of evacuation systems, their full automation and compliance with global safety standards. In this regard, the widespread implementation of digitalized evacuation systems is of great importance not only for saving human lives, but also for increasing the efficiency of emergency management. The introduction of digitalized evacuation systems should be considered not only as a technological innovation, but also as an important factor in shaping a systematic approach to safety management..

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