Research Letter

Design and operational analysis of a three-dimensional urban mobility system for fire evacuation in high-rise buildings

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Abstract

Fire evacuation procedures in high-rise buildings must be designed and implemented with stricter standards than those in ordinary buildings. The basic principles, specific evacuation methods, and new ideas that have emerged in recent years are explained below. The basic rule in case of a fire is not to use elevators. There is a possibility of power outages, smoke spreading, and elevators stopping in the event of a fire. The basic approach is to evacuate vertically using the stairs. The main means of the evacuation is to use the disaster prevention stairs. The following facilities are provided: fireproof and smokeproof structure, emergency lighting, handrails, guide-lights and outdoor stairs. These facilities do not allow smoke to stagnate. Some buildings have floors that can be used to temporarily ensure safety, such as sky lobbies or intermediate evacuation floors. Recent thinking has placed emphasis on fire-resistant/smoke-resistant shafts, the use of emergency power sources, and automatic avoidance of fire floors. An efficient and safe three-dimensional urban mobility system that realizes these functions is proposed in this study. In addition, the distance from the source of the fire to the farthest elevator is derived through a simulation.

Key words
high-rise building fire, vertical evacuation, disaster prevention stairs, disaster prevention elevator, three-dimensional urban mobility system

1. Introduction

The main issue on moving people in high-rise buildings is vertical (up and down) movement. The following issues can be listed regarding the problem of moving up and down inside a high-rise building: (1) There are crowded elevators and long waiting times. The passengers of the elevators tend to be concentrated during peak times such as commuting, leaving work, and lunch breaks. It takes a long time to get to the upper floors, especially in high-rise buildings. (2) Elevator capacity is limited. There is a limit to the number of people who can be transported at one time, so it becomes difficult to process when demand is high. The higher the floor, the more reliant it is on elevators and it becomes difficult to move around by stairs. (3) There are risks in the event of elevator breakdown or disaster. The elevator will be stopped and the evacuation routes will be restricted in the event of an earthquake, fire, or power outage. It is difficult for people on the upper floors to evacuate and there are some safety issues.

The evacuation method in high-rise building fires, which is indicated in (3) are a major social issue. In the event of a high-rise building fire, it is essential to ensure multiple and staged evacuation measures that take into account the height of the building, the number of people present, the attributes of the passengers (elderly, disabled, etc.), and the speed at which the fire spreads. The following describe the typical evacuation methods and their characteristics. (a) Vertical evacuation using stairs: the basic means of escape in a high-rise building fire is through the fire escapes with smoke-proof and fire-resistant construction. The positive pressure smoke control systems and compartmentalization can prevent smoke from entering, and ensure a certain level of safety. In addition, the long-distance evacuation from the higher floors takes time and is physically demanding, and makes it difficult for everyone to evacuate at the same time. (b) Evacuation and emergency elevators: high-rise buildings have begun to install evacuation elevators with fire-resistant and water-resistant structures, emergency power sources, and controlled operation functions in recent years. The installation of this type of elevator allows for smooth evacuation for the elderly and physically disabled. It is necessary to ensure reliability in the event of a fire and to set appropriate operational rules at that time. (c) Horizontal and staged evacuation: A staged evacuation system is adopted utilizing the refuge floors and sky lobbies located at regular intervals in high-rise buildings. Horizontal evacuation on the same floor or to a nearby floor can shorten the evacuation distance and significantly reduce people congestion. (d) Use of external evacuation facilities: external evacuation facilities (e.g., evacuation balconies, rescue bags, and slow descent machines) are effective in low-rise and mid-rise buildings. However, there are some significant restrictions on the installation and operation in high-rise buildings, and they are only used as an auxiliary method. (e) Rescue operation by the fire department: although rescue using ladder trucks and helicopters is important as an external rescue method, their use is limited extremely due to restrictions on the height they can reach and the weather conditions that exist as buildings become taller. It is important to build a redundant evacuation system that combines stairs, elevators, horizontal evacuation, intermediate evacuation, and external support, rather than relying on a single means of evacuation, to improve the safety of fire evacuation in high-rise building.

There are the following representative studies on the movement and evacuation within high-rise buildings, including elevators. The design of the evacuation elevator systems in high-rise buildings is being considered, including human behavior (Nilsson and Jonsson, 2011). The academic discussions cover everything from the traditional stair-based evacuation methods to the system design (including the role of elevators). A comparison of the efficiency of stair evacuation and elevator evacuation was also conducted (Sekizawa and Nakahama, 2011). The comprehensive review was also conducted on evacuation elevators and safe evacuation sites in high-rise buildings focusing on human choices and decision-making methods (Mossberg et al., 2025).

A concept for utilizing a three-dimensional urban mobility system as a means of evacuation in the event of a high-rise building fire is proposed in this study. As a result, a simulation was used to derive the distance from the fire source to the farthest elevator.

The purpose of this study is to overcome the limitations of conventional 'unidirectional vertical (staircase-centered) evacuation' in high-rise building fires by constructing a 'three-dimensional evacuation network' that integrates inter-building and inter-floor movement. Specifically, the aims are as follows:

- Fundamental improvement in evacuation time and safety.
- Transition away from dependence on a single building (toward an urban-scale system).
- Optimization of evacuation through dynamic control (AI and real-time control).

Previous studies can be broadly classified into the following three categories:

- Staircase evacuation models and crowd flow studies (limited to vertical movement and it does not consider structural measures to alleviate congestion).
- Elevator-based evacuation studies (systems confined within a single building).
- Evacuation simulations and disaster prevention systems (based on existing infrastructure with fixed structures).

Furthermore, the novelty of this study can be summarized in the following four points:

- It expands the concept of 'evacuation routes'.
- It represents a shift from 'building-level disaster prevention' to 'urban-scale disaster prevention.'
- It transitions from 'static evacuation' to 'dynamic and adaptive evacuation.'
- It enables universal evacuation.

2. 3D urban mobility system

A multi-story parking system that makes the maximum use of three-dimensional space has been proposed (Funase et al., 2022). Kimura et al. (2024a; 2024b) applied these results and proposed a three-dimensional (3D) elevator system. The 3D elevator system is made up of a skeleton of poles like a jungle gym. The electric boxes that can transport people move up and down, left and right, and back and forth in the system. The electric box inside the 3D elevator system is indicated in Figure 1. It is better to refer to the previous paper by Kimura et al. for details on how the box moves up and down, left and right, and forward and backward. As the box in the 3D elevator system can move using gears, it is stronger than the conventional elevator system which uses metal ropes to move.

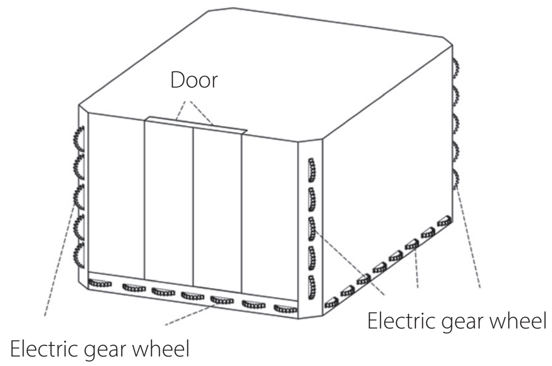

Figure 1: Electric box
Source: Kimura et al. (2024a).

The 3D urban mobility system proposed in this study uses the electric box that can move between a 3D rail-tube (like a tunnel through which the train-rails pass) protecting from fire around the high-rise buildings, as shown in Figure 2. The tube covers the 3D elevator system and it has smoke and fireproof structures. The 3D rail-tube network is basically a system in which elevators for up and down movement are installed at the four corners of a high-rise building, and the movements of the elevators are restricted as follows:

- There are 3D elevators that can move left and right at certain floors (for example, the 11th floor, the 21st floor, etc.).
- And there are elevators that can move back and forth at

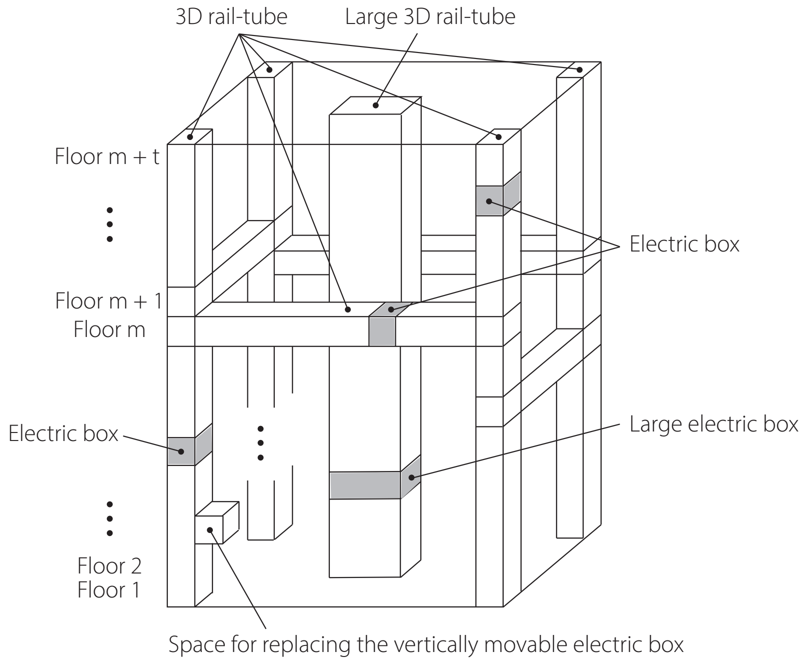

Figure 2: Example of a 3D rail-tube network in a high-rise building

certain floors (for example, the 10th floor, the 20th floor, etc.).

In addition, large 3D rail-tubes that can move up and down are installed in the central axis of high-rise buildings to be used for mass movement of people during commuting, leaving work, lunch breaks, etc., as well as for evacuation in emergencies such as fires and earthquakes.

The functions of the 3D urban mobility system used as an evacuation method for high-rise buildings are as follows:

(1) The electric box is rechargeable and can operate even during a power outage.
(2) The 3D rail-tube and the electric box are smoke-proof and fire-resistant.
(3) The electric box can be operated automatically, manually, or under the control of the control room.
(4) An image sensor is attached to the boarding entrance of the electric box, which can count the number of people waiting for the next one.
(5) When transporting large numbers of people, large electric boxes can be used that run through large 3D rail-tubes. However, its control is only automatic or guided from the control room, and the boxes can only stop at designated floors.
(6) The number of electric boxes and large electric boxes deployed from the hangar connected to the ordinary or large 3D rail-tube can be increased or decreased. In other words, the number of electric boxes increases when the number of people waiting increases, and the number of boxes decreases when the number of people waiting decreases, according to function (4).
(7) The order of the electric boxes that move up and down can be changed. As shown in Figure 2, the method firstly uses the left and right elevators or the front and rear elevators to evacuate one electric box. Meanwhile, the rear electric box is sent forward.
(8) Fire sensors are installed on each floor, and if the opening and closing of the electric box door feels that there is a risk, the box will pass through that floor.
(9) The electric box is equipped with a screen and a speaker that can constantly display the situation and location of the fire. It can also display the evacuation procedures.
(10) The horizontal evacuation from certain floors to adjacent buildings is optionally possible.

Furthermore, this study is at the conceptual proposal stage, and when applying it to actual buildings, there remain various technical and regulatory challenges. The following outlines future issues:

(a) Safety and Reliability:
- Environmental robustness under fire conditions, requiring the system operation in high-temperature, smoke-filled, and toxic gas environments.
- Response to power outages and communication failures, necessitating redundancy in autonomous power supplies.
- Fail-safe and fail-operational design, ensuring that partial failures do not lead to total system shutdown.

(b) Evacuation Control and Operational Algorithms:
- Real-time optimization, requiring dynamic route adjust-

ments according to fire spread conditions.
- Uncertainty in crowd-behavior, requiring responses to panic, counterflows, and congestion.
- Priority control, enabling preferential evacuation of elderly and injured individuals.

(c) Infrastructure Integration (Urban-Scale Issues):
- Standardization of inter-building connections, including unified interface specifications.
- Difficulty in retrofitting existing buildings.
- Challenges in optimizing the network at the city-wide scale.

(d) Regulations and Institutional Framework:
- Compliance with building codes and fire safety regulations.
- Lack of certification systems for evacuation infrastructure.
- Clarification of responsibility and legal liability in the event of accidents.

(e) Cybersecurity:
- Operational disruption due to hacking.
- Risk of cyberattacks during disasters.
- Ensuring the security of control systems.

(f) Human Factors:
- Insufficient user understanding, raising concerns about whether the system can be properly used in emergencies.
- Psychological resistance, including uncertainty about the use of elevators during fires.

(g) Cost and Economic Feasibility:
- Significant increase in initial investment.
- Rising maintenance and operational costs.
- Uncertainty in economic viability.
- Cost-effectiveness concerns if the system is used only during disasters.

etc.

3. Elevator installation location

The method of evacuation from a fire source varies depending on the number of elevators installed and the location. In this chapter, the location of the fire source (assuming one source) and the location of the elevator are derived using random numbers, and the distance from the fire source to the farthest elevator is calculated. The trial will be repeated 1000 times and the average value will be calculated. It takes the value as the answer. The simulation is assumed to be two-dimensional with a square floor measuring 50 m on each side. The simulations are conducted starting with one elevator and gradually increasing the number up to ten elevators, and the results are summarized in Table 1. The calculation flow chart is shown in Figure 3. The reason for selecting the distance to the farthest elevator from the fire source as the evaluation metric is that safety was prioritized over evacuation time. The farthest elevator from the fire source is expected to provide the highest level of safety, as the spread of fire would reach there the latest. However, this assumption is based on the premise that human movement speed is faster than the rate of fire spread.

Table 1: Distance from the source of the fire to the farthest elevator (assume a square floor with each side 50 m)

Number of elevators (*i*)	Farthest distance (MAX)
1	26.4867
2	32.3391
3	35.9540
4	38.1006
5	38.9737
6	40.1011
7	41.0822
8	42.3759
9	41.9997
10	42.9647

4. Conclusion

If the elevator's travel speed remains the same, the ratio of the area required to install the elevator to the area per floor increases, allowing for an increase in the number of people that can travel (per unit time). The '3D Urban Mobility System' is a next-generation evacuation concept that complements and expands on the conventional 'vertical evacuation by stairs' and 'one-way evacuation to ground level' methods used as an evacuation method in the event of a high-rise building fire. Why is the 3D evacuation necessary? This is because in cities high-rise buildings and mixed-use structures are becoming more common and the following issues are becoming apparent:

- The evacuation distance from the floor where the fire occurred to the ground level is long.
- It is difficult for the elderly, disabled, and injured to evacuate using stairs.
- It is difficult and time-consuming for everyone in the building to evacuate at the same time.
- There may be conflicts between firefighting activities and evacuation routes.

In response to above issues, the following idea was conceived, namely '3D movement that includes not only up and down (vertical), but also left and right and front and back'. The 3D urban mobility system is an evacuation and transportation system that integrates 3D transportation which connects the inside and outside buildings, between multiple buildings, and connecting the ground and the outside. It is not a

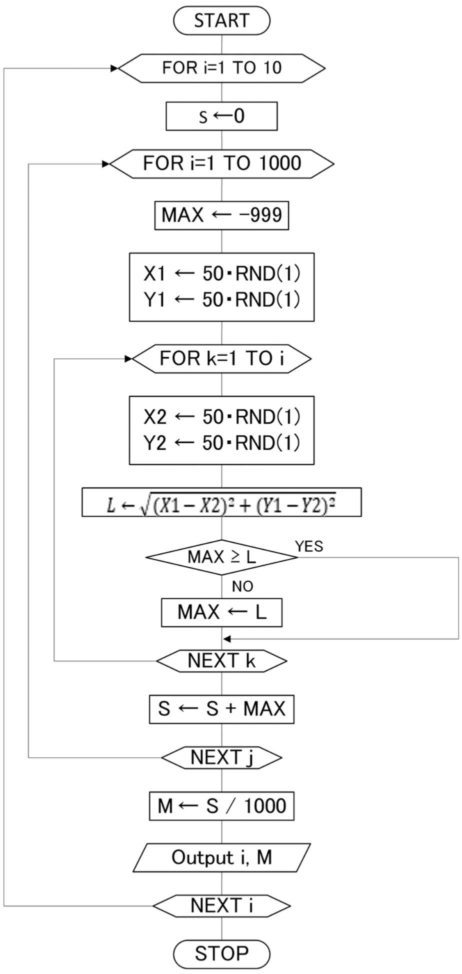

Figure 3: Flowchart for determining distance from fire source to farthest elevator

replacement for the conventional escape stairs and elevators, but an escape route that is dynamically selected depending on the fire situation.

A basic design for a 3D urban mobility system as a means of evacuation in a high-rise building fire, is proposed in this paper. We also conducted simulations to determine the distance from the source of the fire to the farthest elevator. In the future, it will be necessary to build a concrete system based on the results of this study.

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