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Smart Fire Safety Management System (SFSMS) Connected with Energy Management for Sustainable Service in Smart Building Infrastructures

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Abstract: The scale of human accidents and the resultant damage has increased due to recent large-scale urban (building) fires, meaning there is a need to devise an effective strategy for urban disasters. In the event of a fire, it is difficult to evacuate in the early stages due to the loss of detection function, difficulty in securing visibility, and confusion over evacuation routes. Accordingly, for rapid evacuation and rescue, it is necessary to build a city-level fire safety service and digital system based on smart technology. In addition, both forest and building fires emit a large amount of carbon dioxide, which is the main cause of global warming. Therefore, we need to prepare both energy and fire management to achieve carbon neutrality by 2030. In this study, we developed an AI-based smart fire safety system for efficient urban integrated management using a city-based fire safety architecture. In addition, we designed a fire management infrastructure and an energy management system for buildings. The proposal was demonstrated by building a test bed in the A building, and the AR-based mobile/web application was tested for optimized evacuation management. Furthermore, AI-based fire detection and the optimal evacuation of occupants were implemented through deep learning-based fire information data analysis. As a result, this paper presents four points for safety and energy management, and we demonstrate that the optimization of occupant evacuation ability and energy saving can be achieved. We also analyze the efficiency of the data transfer rate to prevent data communication delays by using Virtual Edge Gateway (VEG) management. In the future, we expect that the appearance of future fire and energy management buildings through this research will produce more accurate data prediction technology and the development of cutting-edge smart technology in smart city infrastructures.

Keywords: ICT carbon-neutral platform; smart city; disaster management system; zero-carbon city; urban energy analysis; new energy industry; Internet of Things (IoT)

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1. Introduction

Smart buildings centered on digital technology can be perceived as data-driven buildings. Moreover, these smart buildings can be classified into the following elements: (1) physical building infrastructure management, (2) virtual-based building management, (3) data collection and management, (4) artificial intelligence (AI) and big data, and (5) platform-based integrated building management [1]. Therefore, it is important to analyze the physical and virtual elements in smart buildings, data-based AI technology, and platform-based integrated management of buildings [2]. Therefore, an important element for data-driven smart buildings is optimized building data sharing (such as energy, safety, and physical elements), which can be collected through the IoT sensors [3]. In

Section 1.1, we explain the IoT technologies that are important for data collection and big data management in smart buildings.

1.1. Core Digital Technology of Smart Building: Internet of Things, Big Data, and AI

Smart Internet of Things (IoT) technology is the most important technology element in data collection, where the IoT refers to objects that are connected to the Internet [4]. In a narrow sense, these "things" are simply connected through the Internet, whereas in a broad sense, the IoT can be defined as a technology that provides intelligent value to users beyond the connection between objects and devices through the Internet. In other words, smart IoT is the smallest unit for collecting data in a building, and this building data can be collected through IoT technology [5]. The essential elements that configure the IoT infrastructure in a building system include IoT-based sensors, 5G/6G network equipment, actuators, servers, and gateways [6]. Through these components, data collection consists of three steps: (1) IoT sensor-based data detection, (2) the transmission of the detected data to the smart gateway, and (3) the storage of the data in the server through the smart gateway. For example, consider an IoT sensor system (including temperature, humidity, motion, power, and light sensors) that is built into user A's house to collect data. These IoT sensors are termed environmental information sensors, through which various pieces of environmental information can be collected. These data are then stored in the energy platform (the data server) in real time through the smart gateway.

Big data are defined as technology that involve collecting a large amount of structured and unstructured data from IoT sensors, followed by extracting values from these unstructured data and analyzing the results [7]. Artificial intelligence (AI) is then used with big data to learn through machine learning algorithms, find meaningful values in the data, and make decisions based on the learned results. Accordingly, big data are essential for learning and necessary for obtaining valuable meaning through AI. Moreover, there is a symbiotic relationship between big data and AI. In this study, from a safety perspective, we developed a method for collecting fire-related data from IoT sensors in buildings, after which the current situation can be inferred and predicted. Through this process, rescue managers can identify fire situations using AI-based current situation predictions and then prepare countermeasures for the optimal evacuation of the occupants. From an energy perspective, the most basic and important factor in relation to AI and big data-based energy data analysis would be energy consumption pattern analysis or supply and demand forecasting. Forecasting energy demand is a prediction of how much energy we will use, and forecasting energy supply is a prediction of how much energy can be supplied to users. In Sections 1.2 and 1.3, the necessity for building safety management and energy management systems based on digital technology is discussed.

1.2. Necessity of Building Safety Management System Based on Digital Technology

The safety environment can change significantly due to the large-scale and complex nature of fires, meaning the demand for problem-solving by advanced technical support increases [8]. In addition, as the scope of disaster accidents expands and disaster patterns evolve, it is necessary to analyze and address the causes of disasters.

According to the National Fire Information System statistics of the National Fire Administration of the Republic of Korea, a total of 40,114 fires occurred in 2022, causing 341 deaths, 2321 injuries, and 1.204 trillion KRW of property damage. Compared to the previous year, the number of fires increased by 10.6% (3847 cases), the number of casualties increased by 24.9% (479 people), and property damage increased by 9.5% (KRW 104.9 billion). Among the 341 deaths, 105 (30.8%) were aged 70 years or older, 86 (25.2%) were aged 60–69 years, and 76 (22.3%) were aged 50–59 years. There was a high risk of death from the inhalation of toxic fumes and burns. Deaths occurred due to smoke (flame), making evacuation difficult, or locking exits. The main areas where fires occurred were 14,929 (37.2%) in non-residential facilities, 10,497 (26.1%) in residential facilities, and 4669 (11.6%) in vehicles. Although the overall number of fires in non-residential facilities increased due to increased outdoor activities, the highest number of deaths occurred in residential facilities (216 people) [9].

As the exposure to fire risks and resultant casualties in vulnerable groups (such as the elderly) continues to increase, an AI-based smart fire safety service that can predict the occurrence of disasters to reduce subsequent damage is required [10]. Moreover, the need for smart fire safety services with AI technology based on smart city connections is increasing as the development of optimized smart city infrastructure technology progresses [11]. Since disaster safety R&D is closely related to all fields of science and technology, it is important to connect efficiently with each technology. In addition, the importance of digital twin-based prediction, automation, and simulation technologies that can monitor fire disasters through smart sensors and intelligent recognition systems is increasing. Accordingly, efforts are required to analyze the causes of fires and recognize fire situations due to large-scale fires and irregular occurrences of disasters through this digital twin technology [12]. In this paper, the proposed system is an AR/VR disaster service based on the linkage between the physical and virtual domains inside the building that allows easy and quick evacuation in a space where it is difficult to secure visibility and provides the ability to find occupants in case of a fire in a building.

1.3. Safety, Energy Efficiency, and User Convenience in Buildings

Herein, we propose an application-based fire safety system that can evacuate people to an optimal evacuation location through AR technology in a building. In addition, we propose a smart building system that links safety and energy by linking these smart building elements with a safety system. Accordingly, it is important to understand the connection between safety and energy. Considering this connection, there will be a fire risk for energy storage in the PV + ESS and electric vehicle energy storage devices [13]. Therefore, it is very important to know the risk of fires caused by car batteries and energy storage devices in buildings and prepare countermeasures [14]. It is also important to manage the physical elements of batteries to prevent fires in energy storage devices and to analyze the environment for fire risk prevention. The environmental analysis can be solved by collecting building data and analyzing big data based on AI [15]. In this paper, we present a proposed system built in the A building in Korea after conducting empirical research on smart fire safety services to prepare for disaster safety and implement a smart, safe city. Figure 1 displays a conceptual diagram of the proposal in this paper, and Table 1 lists the differences between the existing and proposed systems.

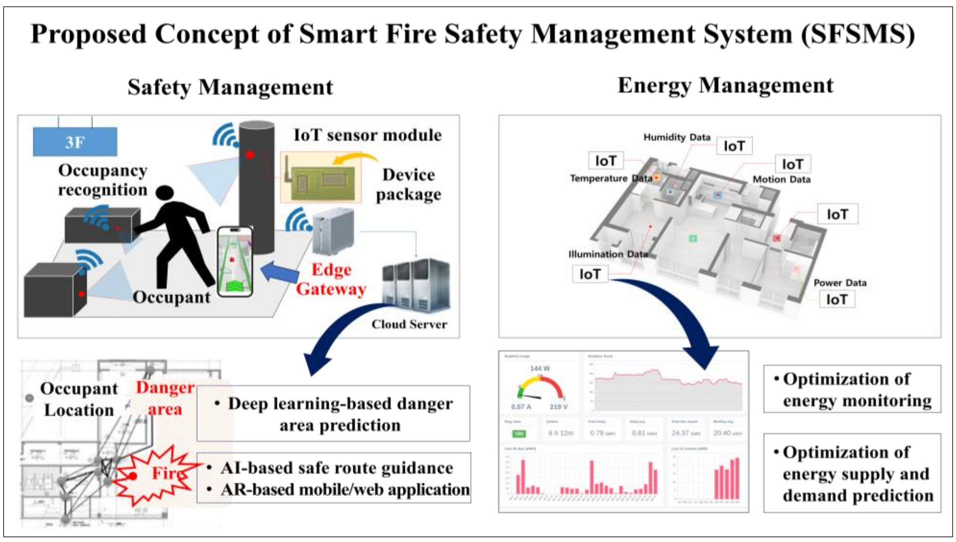


Figure 1. Concept of proposed system.

Table 1. Differences between existing and proposed systems.

Class	Existing System	Proposed System
Service Domain	- Simple independent domain connection (Safety, independent type)	- Safety and energy convergence system service
Discrimination in services	- Occupant application	- AR-based occupant mobile application - Rescuer/manager web application
Network architecture	- Gateway to server, LTE modem to server	- Sensor—Virtual Edge Gateway (VEG)—cloud server - VEG to occupant's app-based real-time fire data transmission
Energy management	- No energy management	- Safety management and optimized energy demand and supply management with HVAC, PV/ESS, data center, sensor management for energy efficiency and monitoring

The key elements of the proposal in this paper can be summarized as follows:

- In Section 3, we introduce the city-based five-layer architecture and present the connectivity of safety management strategy through the five-layer connection method.
- We design a smart fire safety management system (SFSMS) and propose a mobile/web-type application service for an optimal evacuation location in the A building in Korea.
- The proposed system transmits data to the cloud server in real time through the VEG internal network. Reduce the safety data transfer rates and throughput through the VEG.
- We introduce a safety and energy convergence system that is capable of energy monitoring and a safety management system.

2. Related Work

Several recent studies on systems for disaster management have been conducted. We examined related works based on six aspects: (1) fire safety and energy management, (2) fire safety management, (3) mobile applications for fire safety management, (4) BIM-based visualization for fire safety management, (5) wildfire detection using unmanned aerial vehicles (UAVs), and (6) smart energy.

2.1. Fire Safety and Energy Management

Hongqiang et al. emphasized that quick real-time judgment ability and a 5G and IoT technology-based effective fire evacuation system are important for saving lives in fire situations [16]. The authors compared and analyzed various studies that applied IoT technology to safety evacuation systems. Although they did not directly review research that combined safety and energy, IoT data can be used in a variety of ways, such as safety systems in buildings and energy systems. Amandeep et al. proposed an IoT-based cloud-fog-enabled hierarchical evacuation system for large-scale evacuations during emergency situations [17]. Their system utilized the fog computing paradigm to assess panic health conditions in real time. The evacuation system used the fuzzy K-nearest neighbor (FK-NN) method, and the energy-saving mechanism in the fog layer performed data selection and data reduction to reduce the amount of data transmitted to the upper layer.

2.2. Fire Safety Management

Jui-Sheng et al. proposed an intelligent fire management system [18]. In actual fire situations, firefighters spend a significant amount of time rescuing people. However, due to a lack of real-time information, they have to rely on their judgment, which is based on their experience. The time required to rescue people in the event of a fire can be reduced through an intelligent fire rescue system that combines sensors and communication functions to provide real-time information updates, alarm reports, and evacuation routes. In their paper, the location of the mobile phone (user) is determined through the strength of the signal based on a Bluetooth fire detector and a mobile app. However, as the number of fire detection nodes increases, it becomes more difficult to optimize evacuation routes. Accordingly, their proposal compared the characteristics of various route optimization algorithms. Yuxin et al. proposed a concept termed safe fire suppression time (SFT), which combines the characteristics of fire suppression and evacuation behavior to ensure firefighter safety [19]. In addition, the available safe firefighting time (ASFT) and the required safe firefighting time (RSFT) were defined, and detailed calculation methods were provided. The authors also demonstrated the calculation and application of safe fire suppression times through the fire safety performance design of tunnels. Yapin et al. developed a BIM-based fire safety management system platform that considered construction sites [20]. The developed platform included four subsystems, among which the escape route optimization subsystem dynamically optimized the evacuation route by considering the possibility of congestion when people passed through the escape route.

2.3. Mobile Applications for Fire Safety Management

Santiago et al. presented a mobile-based application named Wildfire Analyst™ Pocket Edition, a mobile version of WFA [21] through which firefighters can monitor the expected progress of the fire in real time. Jaziar et al. presented a disaster fire simulation based on participation in a game simulation [22]. The authors tested how the fire situation, temperature, and smoke develop through a smartphone app based on a game scenario. They also evaluated user experiences with this application and presented the advantages and disadvantages of rescue activities. Nikos et al. developed a web/mobile AEGIS platform for wildfire information management [23] in which several tasks can be performed: routing, spatial search for the nearest facilities and fire support infrastructure, accessing meteorological data, and visualizing fire management data (such as water sources, gas stations, and evacuation sites).

2.4. BIM-Based Visualization for Fire Safety Management

Suhyun et al. proposed a building fire information management prototype based on 3D visualization to mitigate fire disasters in buildings [24]. The proposed system provides fire-related information based on BIM technology, enabling emergency responders to identify the location data of indoor facilities. Based on this scenario-based application, a proposed system was demonstrated that contributes to improving rapid access to relevant information. Dahee et al. proposed a BIM-based fire disaster management process that can track building and dynamic fire data simultaneously [8]. For rapid processing, Smart Fire Rescue Management (SFRM) was developed using Revit™ software. The authors conducted a real-case project and an expert survey to evaluate the feasibility of the system. The authors suggested that the proposed system could contribute to accelerating the disaster management process by improving the efficiency of response and rescue in building fires.

2.5. Wildfire Detection Using UAVs

Pietro et al. studied a cyber–physical system for wildfire detection and the early detection of forest fires using a UAV [25]. Here, IoT-based wildfire detection nodes enable early fire detection, enabling continuous monitoring of environmental conditions. When a fire is detected, a UAV can survey the area automatically based on decision-making techniques to find the location of the fire. The authors simulated and demonstrated real-time fire detection capabilities using a forest fire scenario. Rahmi et al. studied a lightweight and attention-based CNN architecture that enables remote control and detection of wildfires using a UAV [26]. Their paper presented approaches such as transfer learning, deep CNNs, and lightweight CNN to perform wildfire detection tasks using images acquired by a UAV camera. In the paper, the authors demonstrated the suitability of an EfficientNetB0-based model for forest fire detection using a UAV.

2.6. Smart Energy

Kadhim et al. studied a method for strategically controlling the clustering and scheduling of IoT sensors to reduce energy consumption while maintaining data transmission effectiveness [27]. IoT sensors can save energy by reducing unnecessary data transmission and data transmission distance by adjusting the number of nodes that consume the most energy during the data exchange process. Hongyu et al. analyzed energy-saving and emission-reduction technologies for the development of smart cities and sustainable low-carbon cities [28]. The authors also compared the energy savings of typical data centers and analyzed the impact of green data centers on global carbon neutrality goals.

3. System Architecture

3.1. Five-Layer Architecture in Smart City for Proposed System

Figure 2 displays the five-layer-based smart city architecture of the fire safety management system, which illustrates the connectivity of the five layers of the proposed system in the smart city [29]. In the services of the building safety system, the most important elements are as follows: (1) detection of the fire area, (2) detection of the fire situation, (3) provision of an optimal evacuation guide, and (4) integrated management of the fire situation. In each layer, these four major services are connected to each other to fulfill their respective roles on a city basis. The following sections present the roles and functions of each layer.

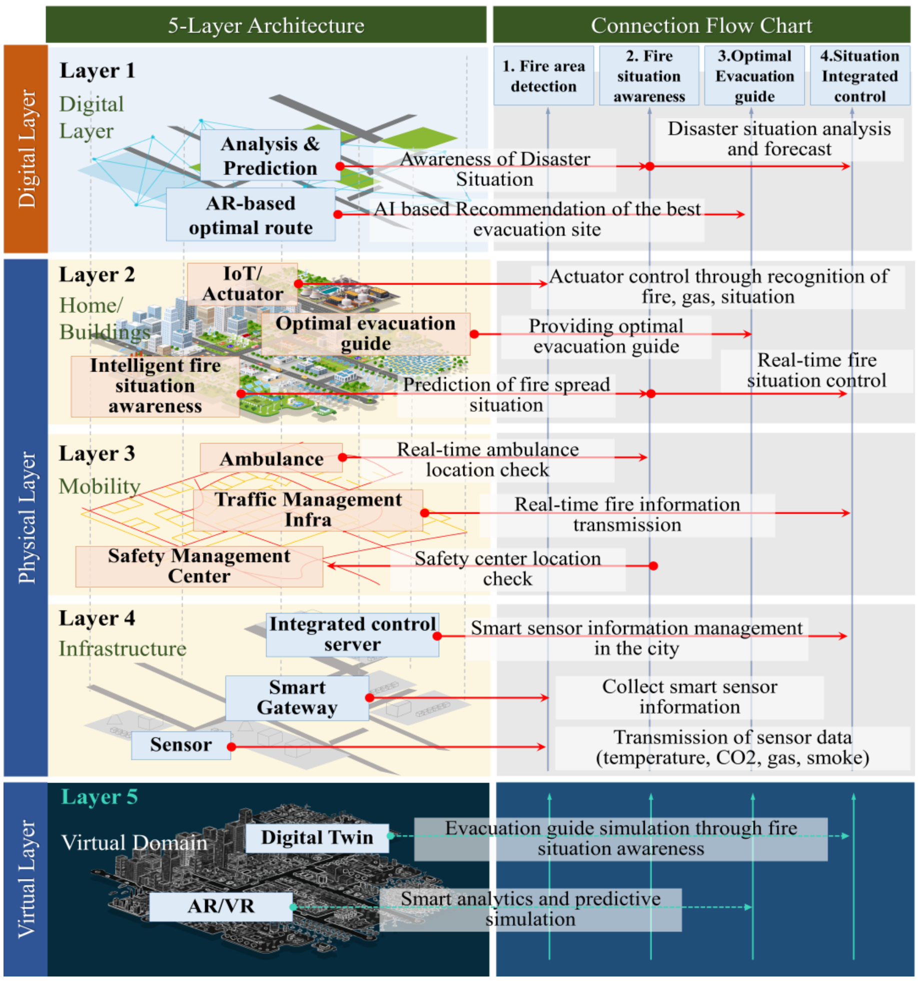


Figure 2. City-based 5-layer architecture.

3.1.1. Digital Layer

The main role of the digital layer is to provide optimal safety services through AI-based data analysis based on fire and safety data received from the city. The proposed SFSMS collects the data through safety management IoT sensors, analyzes and predicts situations for disaster simulation, and provides an AR-based optimal route through the collected data.

3.1.2. Physical Layer

The physical layer can be subdivided into three layers: home/building, mobility, and infrastructure. These are the most basic elements of the physical elements in the city and can provide safety services. The most important elements in the physical layer are IoT and data. The IoT can collect data through various sensors, and it is possible to collect data in various fields through the IoT of the physical layer.

3.1.3. Virtual Layer

The virtual layer is an AR-based optimal safety service layer for providing safety services to users. The virtual layer enables simulation through the digital twin and AR/VR. In this paper, we introduce mobile and web applications to provide an AR-based optimal evacuation route service for building occupants.

We have shown five layers at the city level, and the following section shows the architecture of the proposed system, consisting of three layers.

3.2. SFSMS Architecture

Figure 3 displays the proposed SFSMS architecture, which depicts the connectivity of the three layers (service, platform, and infrastructure layer) of the proposed system. A detailed description of each layer is presented in the following subsections.

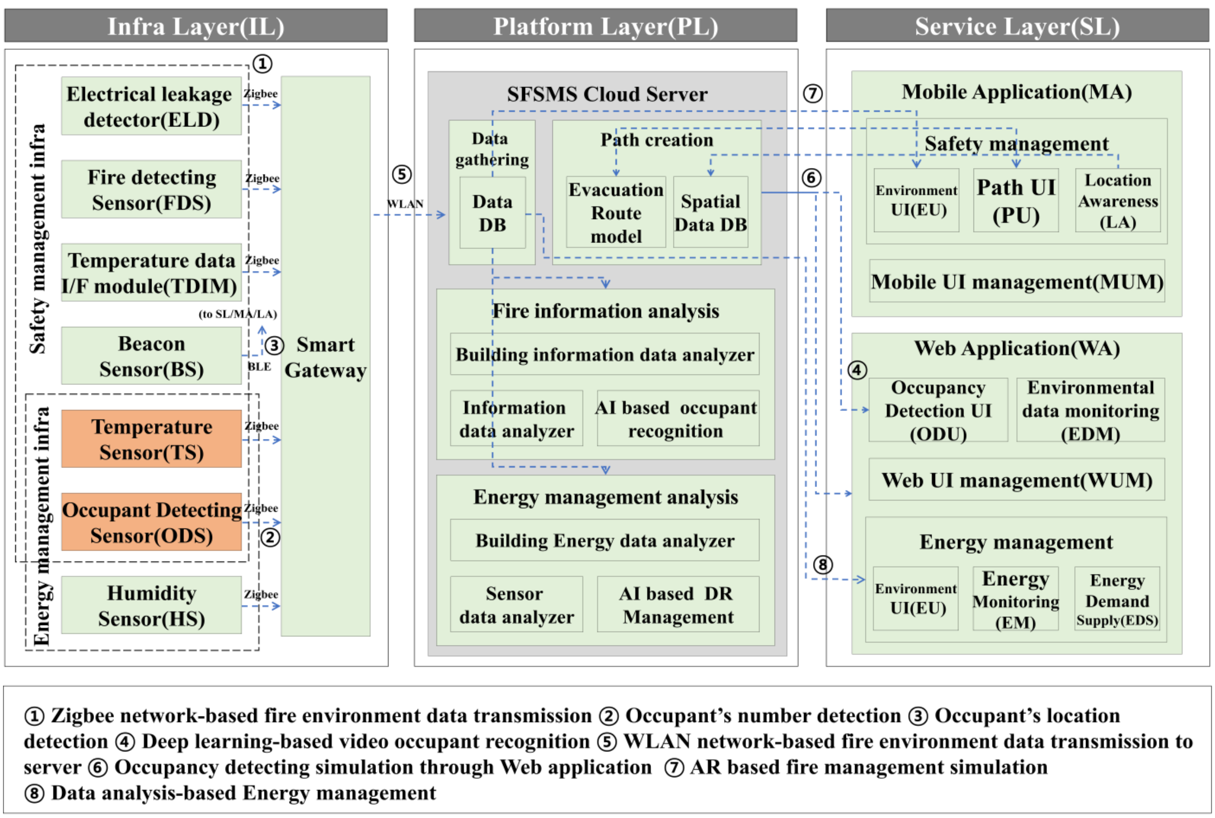


Figure 3. SFSMS architecture.

3.2.1. Service Layer

The main role of the service layer is to provide optimal safety services through AI data analysis based on fire and safety data received from the city [30]. In this layer, the service is provided through the occupant's mobile application and the manager's web application. In the event of a fire in the building, the fire situation is transmitted to the mobile application for occupants so they can evacuate in case of emergency. The web application is managed through a building manager or a rescuer. Through this application, it is possible to monitor the occupant's situation and environmental information.

3.2.2. Platform Layer

The platform layer can be divided into two modules: the SFSMS cloud server and the fire information analysis server [30]. The data collected from IoT sensors are stored in the data gathering DB and provide occupant detection environment information through the path creation module. In addition, the fire information analysis server analyzes AI-based prediction management through occupant location analysis and fire situation analysis from environmental information.

3.2.3. Infrastructure Layer

The infrastructure layer is a distributed IoT sensor layer that provides fire information data to the server [30]. This layer consists of sensors for detecting fire (such as temperature, fire detection, and leakage detection sensors), occupant detecting (such as beacons and motion sensors), and a gateway. The infrastructure layer is divided into safety management and energy management infrastructures. The temperature and occupancy detection sensors are redundant sensors that manage safety and energy simultaneously. Furthermore, the I/F module collects temperature data from the temperature sensors, which are then transmitted to the gateway and server.

4. System and Configuration

4.1. Overview of the SFSMS in the Building Domain

4.1.1. Overview of the SFSMS

This section presents the establishment of a system for a demonstration at the L Building in Seoul, Korea. The status of the SFSMS IoT packages is presented in Table 2 [31]. The service domain was conducted for the first floor of the building, as displayed in Figure 4. The SFSMS IoT packages consist of the fire detection sensor, the integrated manager, and the occupant detection sensor. The SFSMS IoT package's main role is to collect data for providing the safety service [32].

Table 2. SFSMS IoT package configuration in the building.

Class	Item	Contents and Components
Fire detection Sensor	- ZigBee Temperature Sensor	- Room/Basement B1 meeting room installation of IoT Sensor
	- ZigBee fire detection sensor	- Fire detection
	- ZigBee electrical leak detector	- Gas leak detection
Occupant detection Sensor	- Occupant-detecting sensor	- Detecting occupants within the range of the sensing space
	- Beacon sensor	- Beacons to collect user location data
	- Occupancy sensor	- Detection of human body movement using a hot-wire sensor

Table 2. *Cont.*

Class	Item	Contents and Components
Integrated manager	- Temperature sensor I/F integrated manager	- Receives the temperature sensor data through the temperature sensor in real time and notifies the fire situation when the temperature increases due to a fire
	- Smart Edge Gateway	- Direct communication with occupant's app for optimal evacuation - Prevent data transmission delays

(a) Building Appearance (b) 1st floor plan

Figure 4. Building appearance and service domain on 1st floor.

The proposed system can be divided into three fields, as presented in Table 2. There are three areas in the SFSMS: fire detection, integrated management, and occupant detection. In addition, Table 2 presents the IoT sensors used in three fields, while Table 3 displays the actual testbed applied in the proposed system. Figure 4 displays the building's appearance and the 1st floor plan.

Table 3. SFSMS test bed status in the building.

Class	Item
Characteristics	- Building: LH Techno Valley Corporate Support Hub building - Location: Seongnam-si, Gyeonggi-do, Korea - Building area: 11,250.72 m^2 - Number of ground floors: 8 - Number of basement floors: 2
Service Domain	- Service Domain: 1st floor of building

Figure 5 and Table 3 provide the building specifications and a system overview. The overview of the system in Figure 5 is divided into three infrastructures for fire detection: occupant detection, network, and service. This detects fires through the fire detection infrastructure and sends real-time fire situation data to the server. In addition, the location of occupants is transmitted to the server through the occupant detection infrastructure. In the event of a fire, real-time fire information is transmitted to both occupants and rescuers through mobile/web applications for rapid evacuation.

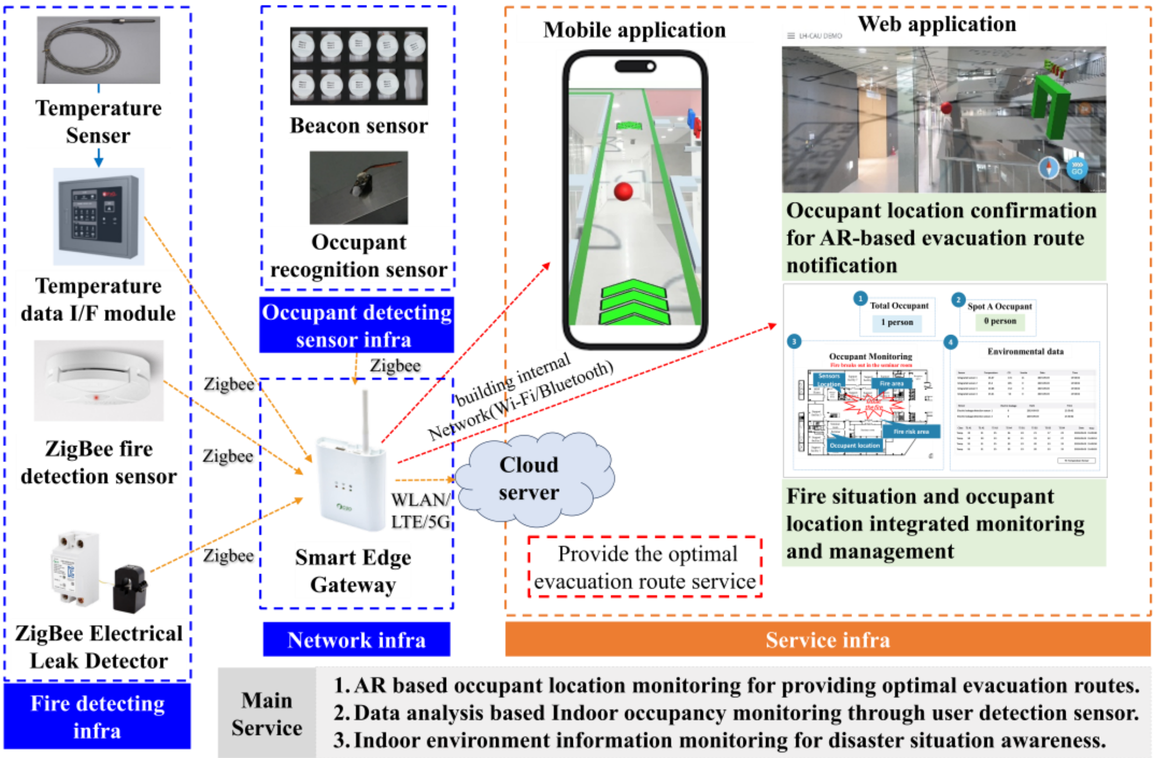


Figure 5. Overview of SFSMS.

4.1.2. Location of Sensors in the Building Testbed

The following shows the analysis of beacon and sensor location coordinates to provide optimal location information. We set the location information through analysis of location coordinates of beacons and sensors so the rescuers can grasp the location of occupants and the fire situation through the web application. Figure 6 and Table 4 display the sensor locations and beacon coordinates.

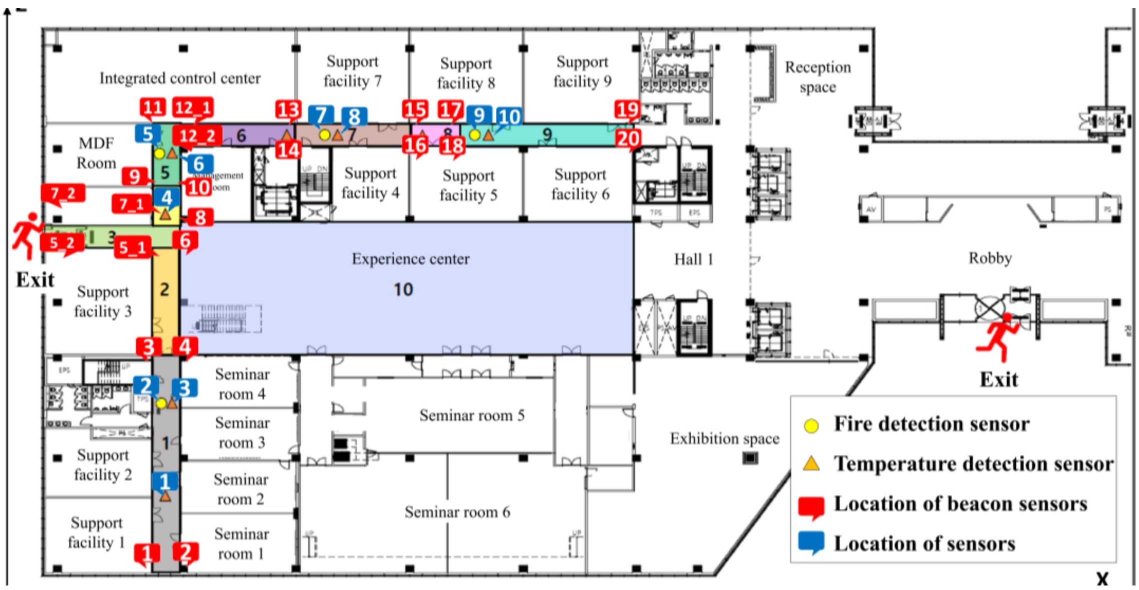


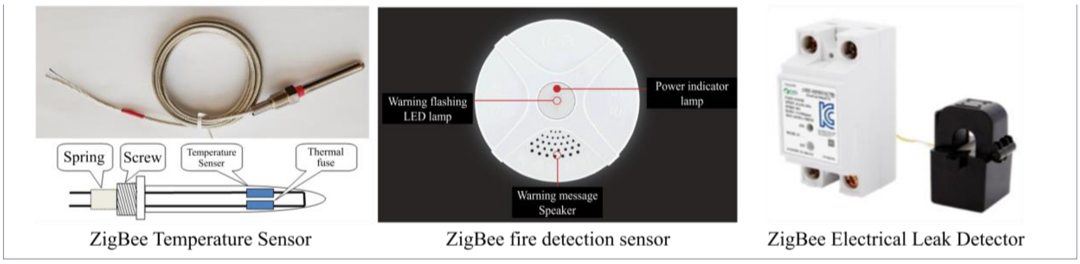
Figure 6. Sensor location.

Table 4. Locations of beacon, fire, and temperature sensors.

Beacon	X	Z	Beacon	X	Z	Sensor	X	Z
1	23.83	10.72	11	23.83	69.21	1	25.18	20.6
2	26.54	10.72	12_1	26.54	69.21	2	24.18	32.83
3	23.83	38.91	12_2	26.54	66.27	3	26.18	32.83
4	26.54	38.91	13	38.17	69.21	4	25.18	57.61
5_1	23.83	52.82	14	38.17	66.27	5	24.18	63.88
5_2	13	52.82	15	49.38	69.21	6	26.18	63.88
6	26.54	52.82	16	49.38	66.27	7	41.67	66.74
7_1	23.83	55.77	17	54.63	69.21	8	41.67	68.74
7_2	13	55.77	18	54.63	66.27	9	55.34	66.74
8	26.54	55.77	19	72.39	69.21	10	55.34	68.74
9	23.83	60.98	20	72.39	66.27	-	-	-
10	26.54	60.98	-	-	-	-	-	-

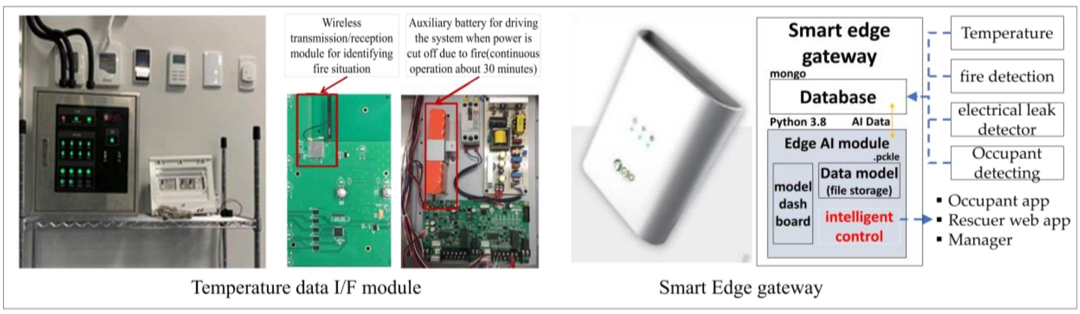
4.2. SFSMS IoT Devices (Infrastructure Layer)

Figure 7 and Table 5 display the SFSMS IoT package (fire-detecting sensor infrastructure, occupant-detecting sensor infrastructure, and integrated manager) configuration in the building.



(a) Fire detecting sensor infra

(b) Occupant detecting sensor infra.



(c) Integrate manager

Figure 7. Fire detection sensors.

Table 5. SFSMS IoT devices (infra layer) in the building.

Class	Sensor	Field	Details Specifications	
(a) Fire detecting sensor infra.	ZigBee Temperature Sensor	Safety Energy	Thermal fuse	- DF128S, DF192S, DF240S
			Sensor	- MF58 104F3950 (NTC Thermistor)
			Measurement performance	- ±0.5%: Ta = −9 to +47 °C - ±1.0%: Ta = −55 to +81 °C
			Thermal fuse characteristics	- Thold = 80 °C, TFUSE = 104 °C - A protection device to prevent temperature sensor impulse errors in sudden temperature changes.
			Metal material	- SUS304
			Insulation material	- GD#3(magnesia)
			Wire material	- RTD W 0.3 SQ
			Operating temperature	- −55 to +200 °C
			Size	- Sensor part: 60 × Φ8 [mm] - Joint: PT1/4 - Hexagonal nut part: 9.5 × Φ16 [mm] - Wire length: 3000 [mm]
	ZigBee Fire detection sensor	Safety	Sensor	- Photoelectric smoke detection sensor
			Performance	- within 0.5 s
			Operating power	- AC Adapter—220 Vac input/+12 Vdc output
			Texture	- Poly Carbonate (V-0)
			Operating temperature	- +100 °C Max.
			Weight/Size	- 190 g/109 (C) × 33.65 (H) [mm]
	ZigBee Electrical Leak Detector	Safety	Characteristic	- Always measure power consumption of AC power and collect power measurement values at desired times. - Prevent fire by notification in case of leakage
(b) Occupant Detection Sensor	Occupant recognition sensor	Safety	Operation method	- For counting the number of occupants. - Infrared communication detects occupant movement - Counts occupants by distinguishing between entering and leaving the room.
	Beacon sensor	Safety	Operation method	- Finds the location of a user with a smartphone within a radius of 50 m. - Bluetooth-based low-power communication
	Occupancy sensor	Energy		- Personnel location detection sensor

Table 5. *Cont.*

Class	Sensor	Field	Details Specifications	
(c) Integrated manager	Smart Edge Gateway	Safety Energy	Network type	- Ethernet IEEE 802.3 10/100 Mbps
				- Wi-Fi IEEE 802.11 b/g/n
				- Zigbee IEEE 802.15.4
			Encryption method	- 128-bit symmetric key block encryption method (AES-128) data encryption
	Temperature data I/F module	Safety	Total weight	- 21.2 kg
			Radiation time	- 60 s
			Working pressure	- 1 MPa
			Operating temperature	- −20 to +50 °C

The following subsection describes the sensors displayed in Figure 7 and Table 5.

4.2.1. Fire Detecting Sensor Infra.

The ZigBee temperature sensor consists of a temperature measurement sensor comprising a negative temperature coefficient (NTC) thermistor, a thermal fuse in the form of an organic thermal element as an explosion-proof shield, and a ZigBee communication module. It is installed in a home or building and operates with the goal of developing a function that can help with fire extinguishing and evacuation activities by transmitting the ambient temperature to a smartphone or PC with an application installed through a smart ZigBee communication interface module when a fire occurs [33]. This sensor transmits the measurement result of the smoke detection sensor to the smartphone or PC where the application is installed through the ZigBee communication interface module. The ZigBee electrical leak detector was developed with the goal of helping to prevent accidents such as fires caused by short circuits when an electric leakage occurs by installing it at the circuit breaker terminal of a distribution board in a home or building. It notifies the smartphone or PC where the application is installed through the smart ZigBee gateway as a notification function.

4.2.2. Occupant Detecting Sensor Infra.

The proposed paper displays an intelligent occupant recognition system for detecting the situation of occupants. It is an intelligent occupant recognition system for determining occupant location in case of fire. Occupancy sensors are used to detect user behavior patterns in an energy management field. The list of intelligent occupant recognition sensors is presented in Table 5.

4.2.3. Integrated Manager (Temperature Data I/F Module, Smart Edge Gateway)

We developed a temperature data I/F module that receives the temperature sensor data in real time and notifies the fire situation to the building manager when the temperature increases due to a fire. A temperature data I/F module detects fire situations by analyzing the temperature data. The smart edge gateway collects data from the temperature, movement, fire detection, and electrical leak detector sensors and delivers information directly to the occupant app in the event of an emergency [34]. The gateway collects information from the ZigBee-based sensors and provides information to servers and occupant apps through wired LAN communication and Wi-Fi.

4.3. SFSMS Platform (Platform Layer)

Cloud-Based Web Server for SFSMS

In this section, we demonstrate a cloud-based web server for SFSMS that collects and stores environmental data, including the fire ignition point, temperature, and occupant locations [35].

- Cloud server: Instance A

The system elements receive environmental data through the RESTful API provided by the gateway and periodically store them in its own database. When a mobile application receives a request for environment data transmission, it transmits the requested data from its own database through API_A in RESTful form. If specific environmental data among the periodically stored environmental data indicate a fire situation, a notification is sent to the mobile application through the PUSH message function. The features required for this are as follows:

  - Environment data collection cycle setting function;
  - Periodic data collection function through API (such as temperature, CO, and smoke);
  - API_A function that can handle requests of mobile applications and Instance B;
  - Fire situation recognition function through environmental data;
  - PUSH message notification function to mobile application when fire situation is recognized.

- Cloud server: Instance B

A member of the system periodically creates or updates an evacuation route generation model through unsupervised learning with data such as the fire ignition point, ignition point temperature, and occupant locations. It transmits and receives data in real time through mobile and web applications and the Socket.io method. This checks the status of personnel in the space through the location data received from the mobile application. In the case of a fire, it receives environmental data through API_B in RESTful form from the mobile application. Then, it derives an evacuation route through environmental data and location data in the evacuation route generation model and transmits this to the mobile application. The features required for this operation are as follows:

  - Evacuation route model generation cycle setting function;
  - Periodic generation or renewal of evacuation route through unsupervised learning method;
  - Ability to process requests from mobile applications through Socket.io;
  - Real-time communication function through mobile and web applications and Socket.io;
  - Environment data request cycle setting function.

4.4. Service Configuration (Service Layer)

In this paper, we propose an AR-based mobile application and web application. The mobile application enables an AR-based occupant situation analysis and fire situation monitoring. In addition, it is possible to check the number of occupants and apply occupant tracking technology with this application. The mobile-based application service is a service for occupants that helps them to escape easily from their location based on the mobile application in the event of a dangerous situation.

The web application has functions for building managers and rescuers and an interface that can check the location data of occupants and the number of occupants in real time in addition to visually checking occupants. Accordingly, it allows rescuers to easily locate the occupants. The picture below displays the AR-based mobile applications and the web applications. Figure 8 displays the mobile application UI and the web application UI. In the mobile application, it is possible to display the optimal evacuation route in case of an emergency, as presented in Figure 8a (mobile application), and there is a function to monitor environmental information, as displayed in Figure 8b (web application).

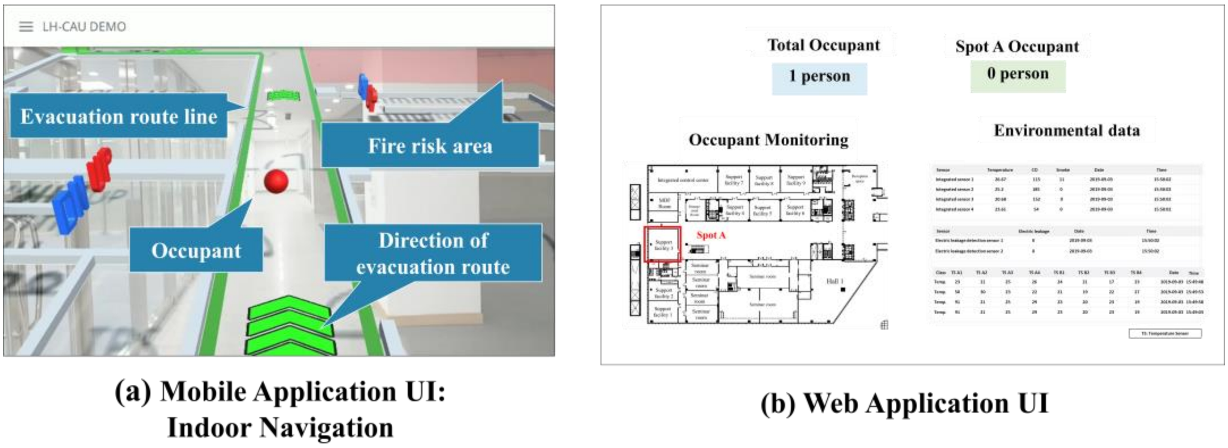


Figure 8. Mobile and web applications.

5. System Control Process

5.1. Main Service Configuration

5.1.1. AI-Based User Location Detection

In the study, we researched an AI-based occupant situation analysis method and developed fire situation monitoring through a web application, with which it is possible to check the number of occupants indoors and track their behavior. Figure 9 presents the system flow for checking occupants and monitoring environmental information. Figure 9 also displays the state of the system in standby, while Figure 10 is the active_normal state in the case of a normal step. In the case of active_normal, it is possible to monitor the environmental data collected by the environmental information sensors and monitor the current location and number of occupants in the building. Furthermore, at this stage, it is possible to check the building energy data for energy efficiency. This field will be described in detail in the following section.

- System state: standby
- System status: active_normal (monitoring the current environment information and checking the energy status information)

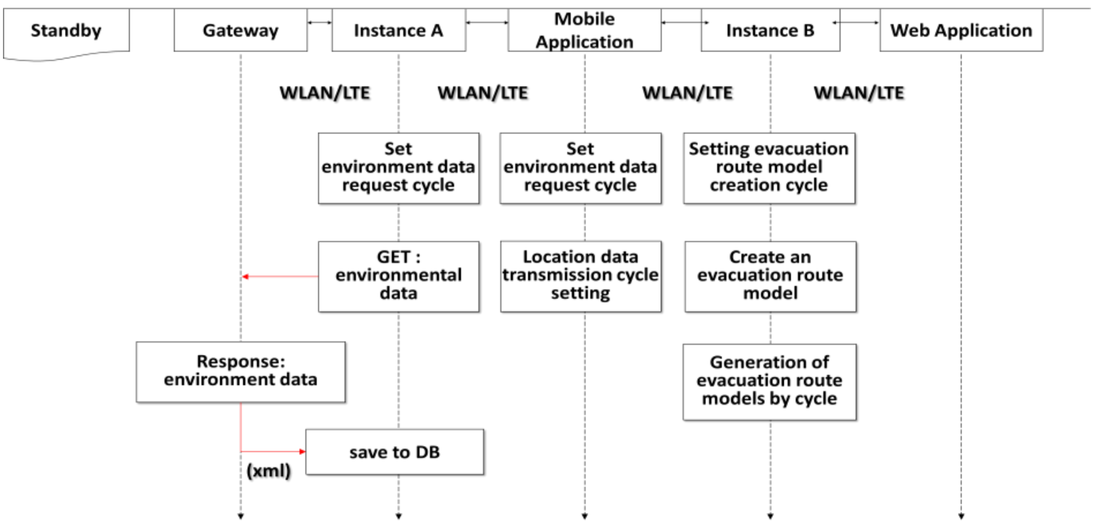


Figure 9. System state: standby data flow.

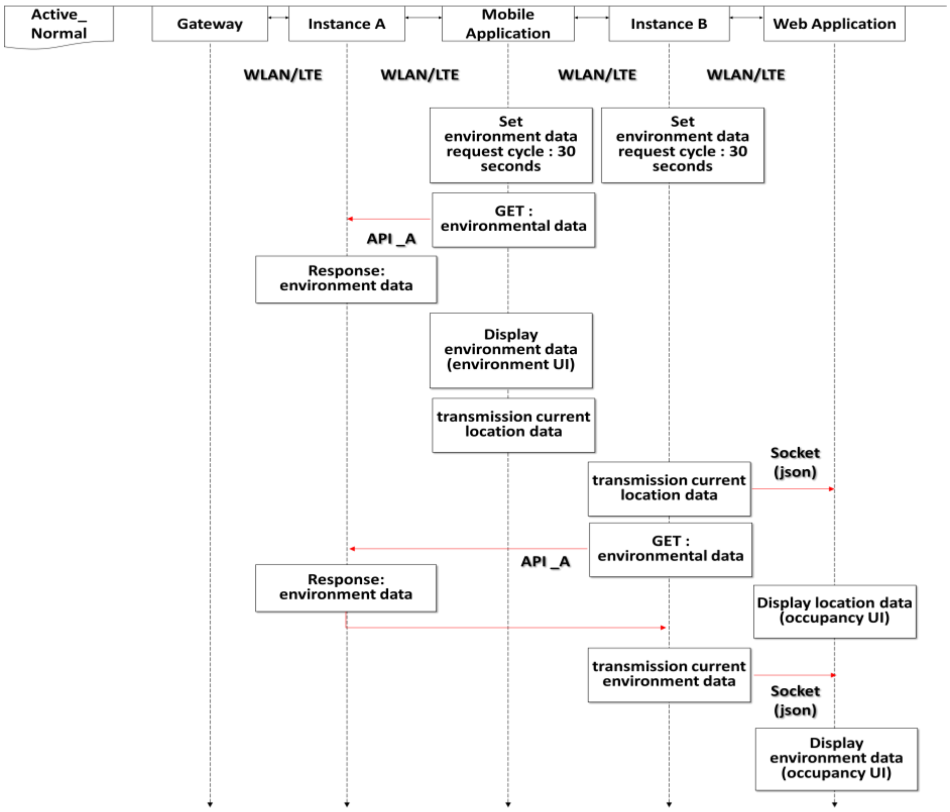


Figure 10. System status: active_normal data flow.

5.1.2. Data Analysis to Provide Optimal Evacuation Guide

In preparation for fire situations that could occur in buildings, it was necessary to learn a deep learning model that can detect flames and fires. Real-time fire detection is possible based on the trained fire detection deep learning model. In addition, location data is analyzed through location-by-zone and sensor coordinate analysis. In addition, the server analyzes location data by examining the location by area and sensor coordinates. Figure 11 displays the system flow in the case of a fire.

- System status: active_fire

The following bullet points describe the deep learning-based fire situation detection and evacuation route creation process through environmental data learning:

- Fire situation detection: The temperature/fire sensor installed in the room detects a fire situation under certain conditions. (Current conditions: when detecting a temperature $\geq$60 °C).
- Fire situation notification: Notifies of the fire situation through mobile application and web dashboard via a PUSH message. (Simultaneously, it is possible to contact related organizations, such as fire departments).
- Delivery of environment/location information: When the occupant checks the fire notification and runs the mobile application, the current location and environment data are delivered to create the optimal evacuation route.
- Display of occupant location and environment information for rescuers: The current location of the occupant and environment data are displayed periodically. (Current cycle: 5 s)
- Create an optimal evacuation route considering the current location of the occupant and the fire situation through an evacuation route generation model created by learning factors such as the location and environmental data. In addition, the model can create a more accurate evacuation route as more actual data are accumulated. The model is created by learning data derived through simulation.

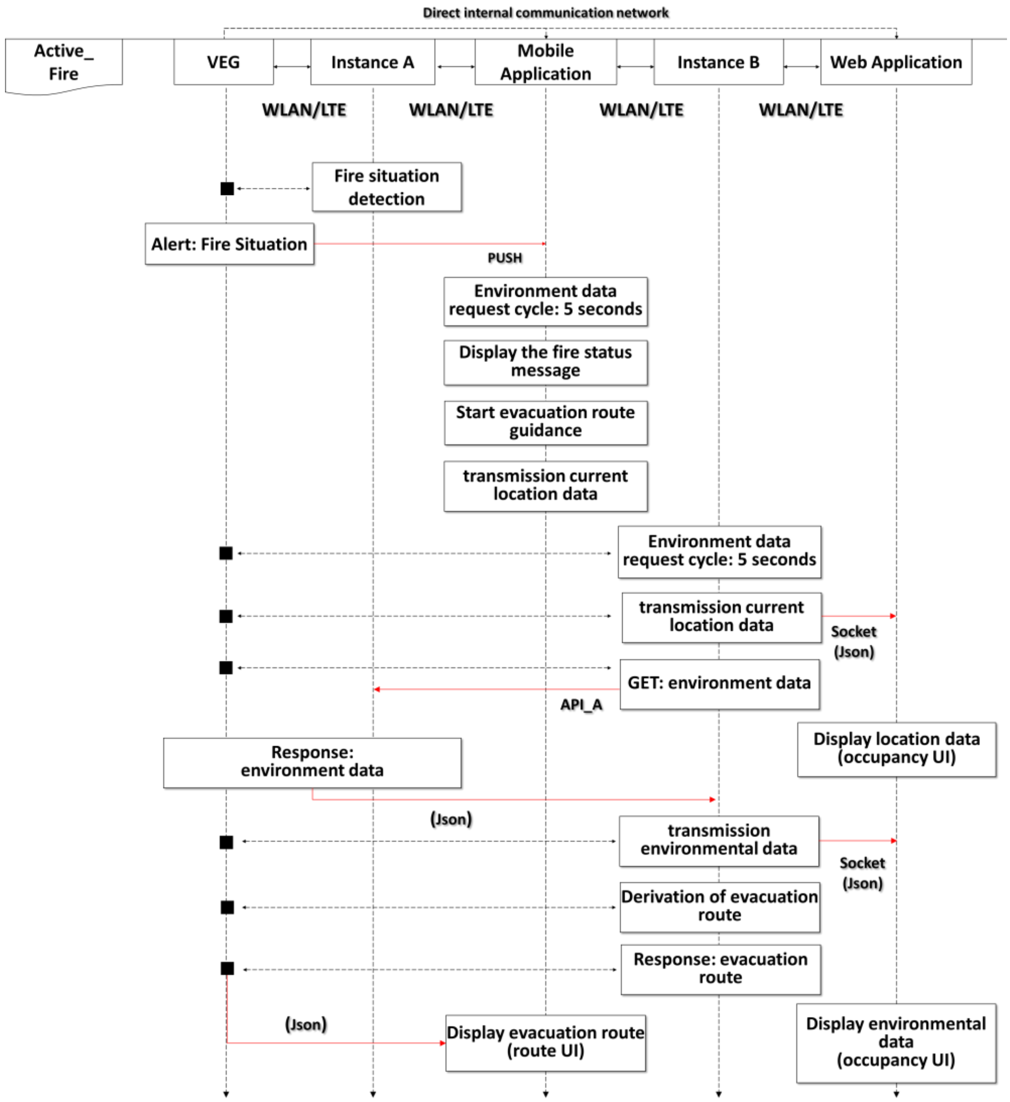
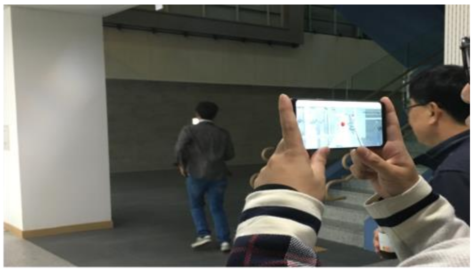


Figure 11. System status: active_fire data flow.

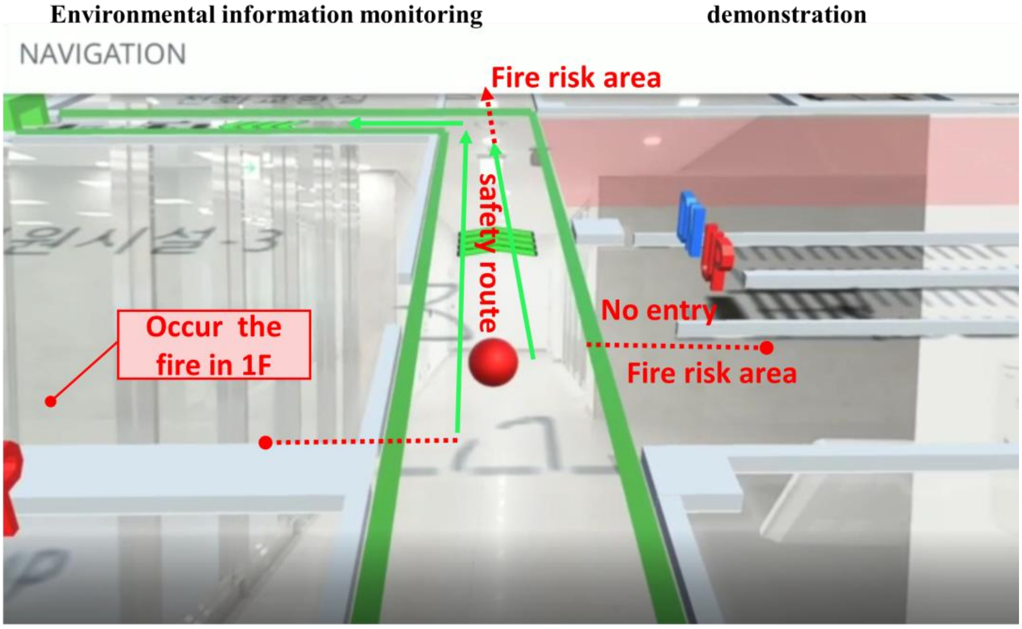
5.1.3. AR-Based User Mobile Application

This paper demonstrates a smartphone-based emergency evacuation application for user optimization for quick response in crisis situations. This is an AR-based mobile application that enables monitoring of environmental information and determining the location and number of occupants. Then, it provides optimized evacuation guide information in the case of a fire [36]. Figure 12 displays the mobile application UI and the test bed demonstration screen. The proposed system can monitor environmental information (Figure 12a), including temperature, humidity, and power, in terms of safety and energy. The mobile application UI of the optimal evacuation route is displayed in Figure 12c. It collects environmental information and analyzes the collected data based on the AI to provide a guide for optimal evacuation.

(a) Mobile Application: Environmental information monitoring



(b) Mobile Application: Test bed demonstration



(c) Mobile Application: Check fire risk areas and evacuation routes

Figure 12. Mobile application UI.

5.1.4. Integrated Control Web Application for Administrators

Figure 13 portrays the proposed system data flows, and Figure 14 depicts an AR-based occupant situation analysis and fire situation monitoring web application applied with indoor occupant identification and occupant tracking technology. This platform has a web dashboard interface that can check the location and number of occupants in real time through the received data.

The details of the interface are as follows.

- Total number UI: It is possible to check the total number of people who are currently running the mobile application and the number of people in Support Facility-3.
- Support Facility-3 Personnel UI: This can check the number of personnel inside Support Facility-3 through the sensor installed at its entrance.
- Occupant tracking UI: This can check occupants and sensor locations in the building. If a fire occurs, it is possible to check the fire area and the danger area of the fire.
- Environmental data UI: This can periodically check information such as temperature/CO/smoke/electric leakage from installed sensors (current cycle: 5 s)

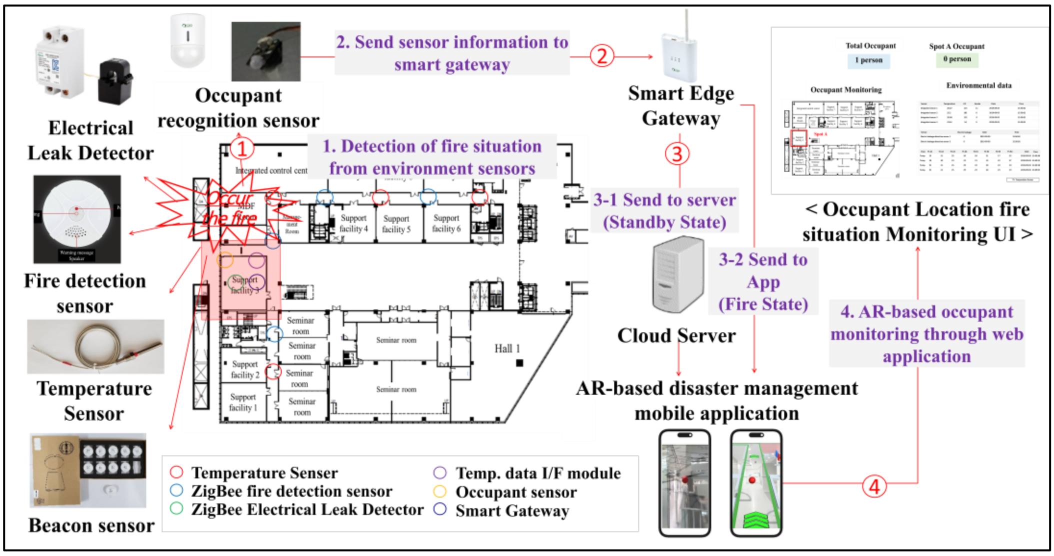


Figure 13. SFSMS mobile/web application data flow.

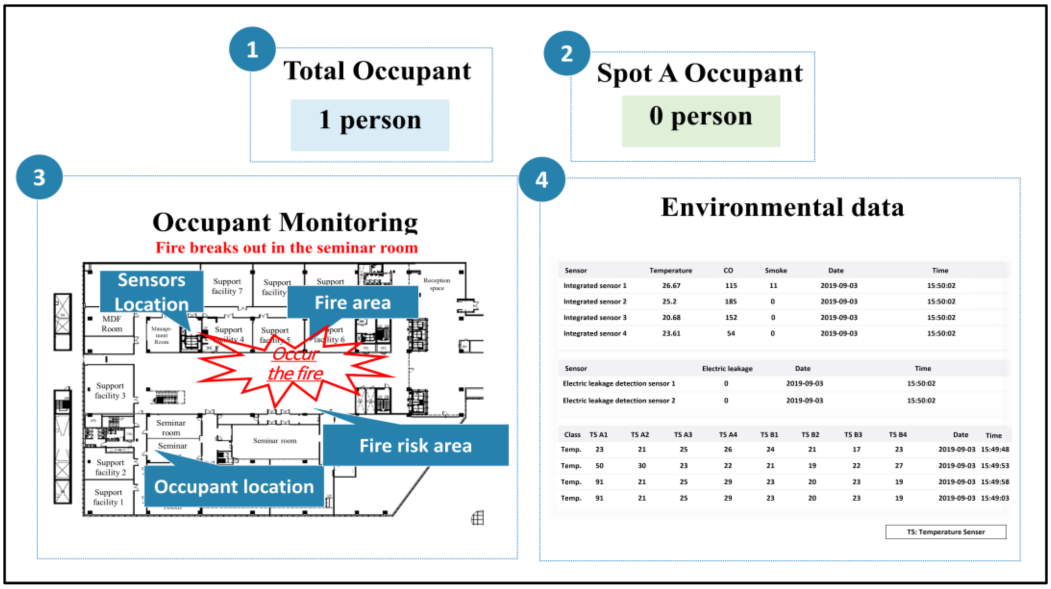


Figure 14. Web application UI: integrated control platform for administrators.

5.2. Energy Management Platform Connection Control

This system is designed to monitor the energy status during normal times while simultaneously functioning to detect the situation in the event of a fire. It is possible to monitor the environmental data monitoring as energy consumption in a building through the web application presented in Section 5.1.4. The IoT sensor presented in the thesis can collect data from the safety and energy aspects. We analyze the relationship and detailed process between the SFSMS system and energy in the Discussion section.

6. Discussion

6.1. Fire Situation Prediction and Energy Demand/Supply Prediction Mechanism

Figure 15 displays the SFSMS safety and energy management mechanism. The top of Figure 15 demonstrates that the safety management system provides optimized evacuation guidance by predicting fire safety situations based on a safety data analysis [30]. Simultaneously, the system manages the energy, as presented in the bottom part of Figure 15.

Energy management mainly comprises managing the HVAC, PV, and ESS and is operated in connection with the safety system when a fire occurs.

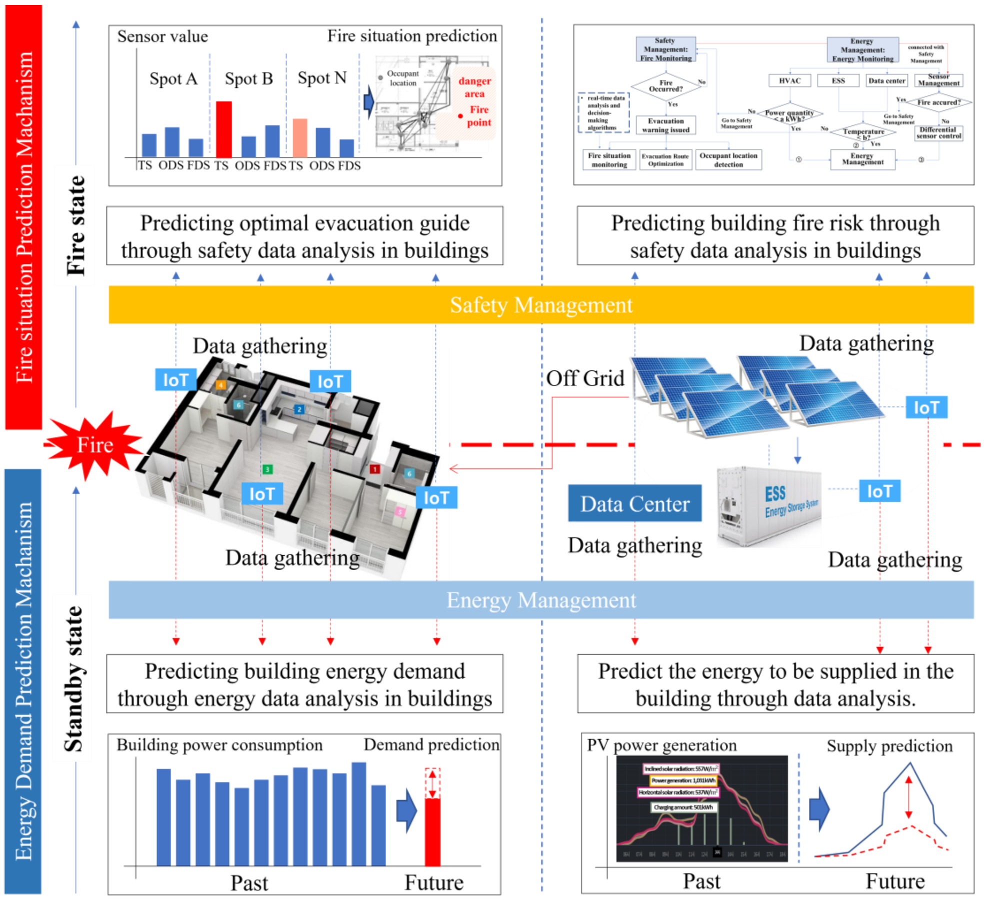


Figure 15. SFSMS safety and energy management mechanism.

6.2. Analysis of the Relationship between Safety and Energy Management in the SFSMS

This system operates as a fire detection system in crisis situations while simultaneously performing energy-saving operations during normal times. Next, we analyze the connectivity between the safety and energy systems and propose a smart and intelligent building system. Figure 16 displays the system integration process connecting the SFSMS and energy field. The explanation of Figure 16 begins in Section 6.2.1.

6.2.1. Analysis of the Safety Management in the SFSMS

The safety management aspect is divided into two stages: standby and active. The active part represents a situation where a fire has occurred in the building. The standby process is described as follows:

- Sensing: Sensing in the safety management system is performed during normal times. At this stage, the sensor detects whether there is a sudden temperature change in advance to prepare for a fire situation [37]. The server receives real-time information from various sensors (such as temperature and occupancy) and determines whether there are any safety problems. In addition, it monitors energy related to sensors, including temperature, occupancy, and humidity.
- Monitoring: In the monitoring stage, the server integrates and monitors real-time temperature data during normal times. If there is a rapid temperature change detected through temperature monitoring, it is highly likely that an emergency has occurred. In the sensing and monitoring phases, accuracy is more important than speed because they are normal detection phases.

The active fire process is divided into four stages (detection, environment analysis, extinguish, and rescue), as follows:

- Detection: In the detection step, when a fire situation occurs, it is detected by the sensors and then transmitted to the server, from which occupants and administrators are notified of an emergency. At this stage, it is necessary for the sensor to detect the fire situation and quickly deliver it to the server. From this stage, promptness for rapid evacuation is very important.
- Environment analysis: This stage involves collecting data on fire information and predicting fire information inside the building based on the collected data. This is a very important step because the current fire situation must be quickly identified and communicated.
- Extinguish: This is the evacuation phase, in which occupants must quickly evacuate through a mobile application. The server transmits the fire situation and the optimal evacuation route to the application after analyzing the environmental information. The occupants then confirm and evacuate through the application. At this stage, the usability of the application is very important.
- Rescue: In this stage, the role of rescuers is important, and they can locate occupants through a web application.

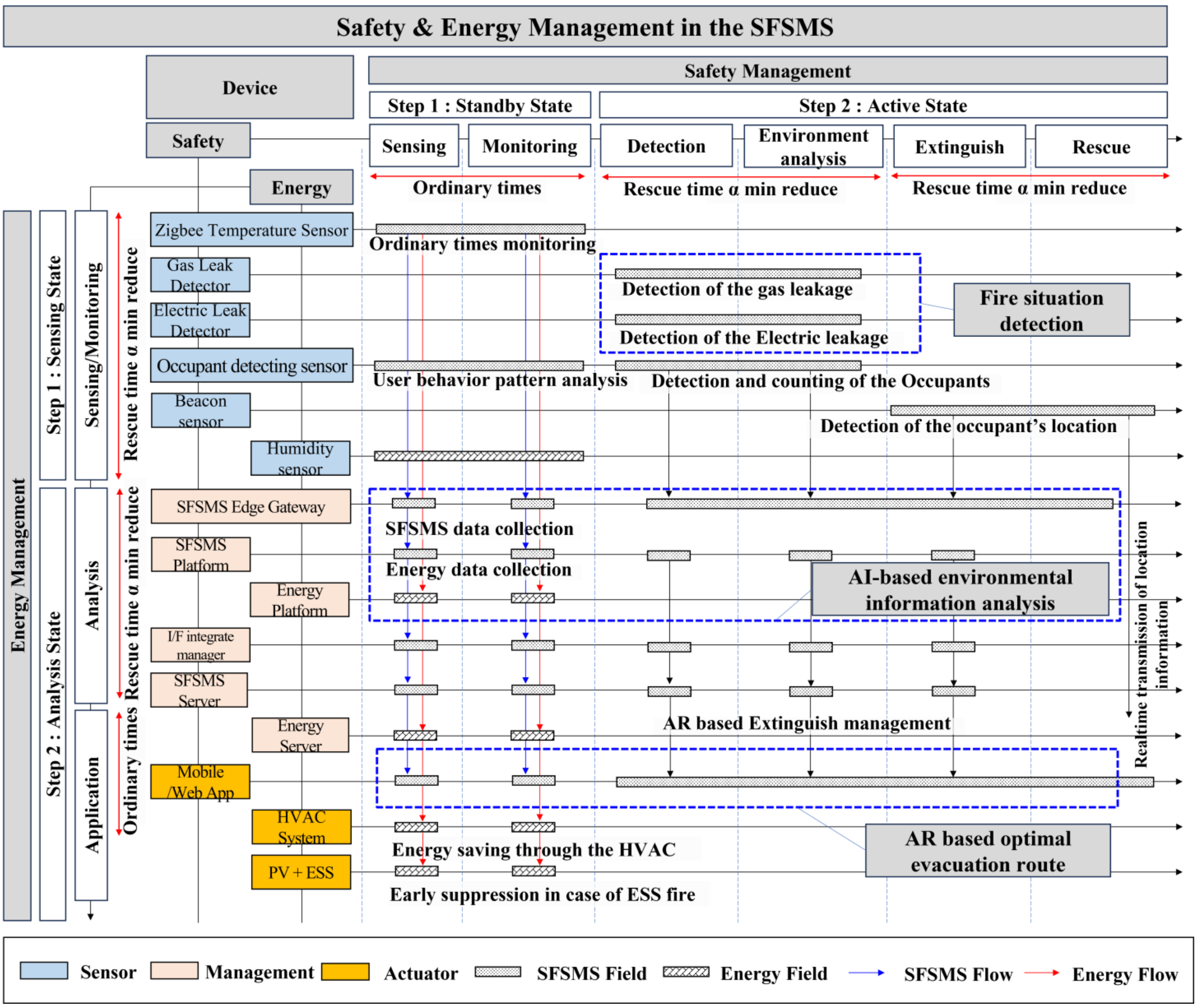


Figure 16. SFSMS process, including safety and energy management.

6.2.2. Analysis of Energy Management in SFSMS

Energy management is divided into two stages: sensing and analysis. These stages are further divided into sensing and monitoring fields during sensing and analysis and application fields during analysis, as follows:

- Sensing/Monitoring: Sensors related to energy suggest temperature, occupant detection, and humidity sensors [38]. The temperature/humidity historical data are collected to predict the future temperature/humidity, and the movement of the occupant is detected through the occupant-detecting sensor and the predicted behavior patterns.
- Analysis: This is a predictive analysis stage for energy saving through the collected data. Here, it is possible to predict future demand/supply energy consumption by analyzing the data patterns of stored energy data from the past. The key point of AI and big data-based energy data analysis technology is to predict demand and supply by analyzing the consumption patterns of energy data for energy supply stability and energy cost savings in the analysis stage.
- Application: The application field can be regarded as an application or actuator that can apply energy services [39]. In the buildings, energy data (such as the power demand of HVAC systems) will be collected through the IoT and stored in a server. Here, it is possible to predict future demand-side energy consumption by analyzing patterns of energy data stored from the past. In addition, it should be possible to predict how much energy can be supplied to the demand side through PV supply forecasting.

6.2.3. Scenario Simulation of Safety and Management in the SFSMS

This section presents the integration of the SFSMS control process scenario with safety and energy management. Figure 17 displays the integrated algorithm that portrays the linkage between safety management, energy management, and the integrated platform.

The following bullet points describe the detailed sequence of a safety and energy management control process scenario in the SFSMS, as presented in Figure 17.

- Safety Management: (1) (Sensing) The air conditioning system is an actuator with a plugged-in IoT sensor that transmits power information from the IoT sensor to the server. (2) (Monitoring) The SFSMS server monitors energy and simultaneously determines whether there is a risk of fire due to overcurrent. (3) (Monitoring) At this stage, the server performs energy monitoring for energy saving and monitoring for fire safety. (4) (Detection) When a fire occurs due to overcurrent in a building, the server determines that a fire has occurred and delivers the fire situation to occupants and rescuers. (5) (Rescue) The occupants evacuate through the mobile application, and the rescuer determines the current locations of the occupants through the web application. The server delivers the current fire situation in real time to occupants and rescuers. (6) (Extinguish) The occupants are evacuated through an application that provides optimal evacuation and rescue routes.
- Energy Management: (1) (Sensing/Monitoring) The ESS has plugged-in IoT sensors and transmits data (such as temperature, charging amount, and charging time) from the IoT sensors to the server. (2) (Energy analysis) The server monitors the energy and analyzes the temperature to determine whether there is a fire risk in the ESS. (3) (Detection) In this step, the risk of fire is detected, and the current situation is communicated to occupants and the manager's mobile/web application. If a fire occurs due to an ESS explosion, go to Step 5 of SFSMS management, as suggested previously.
- Integrated Management: This refers to the integrated management of all areas, such as system safety and energy. The sequence presented in Figure 17 is as follows. (1) (Sensing) The IoT sensor built into the data center detects the temperature in the data center and transmits it to the server. (2) (Monitoring) The server determines whether there is a risk of server explosion due to the temperature increase. If there is a fire due to a server explosion, go to step 5 of the SFSMS management.

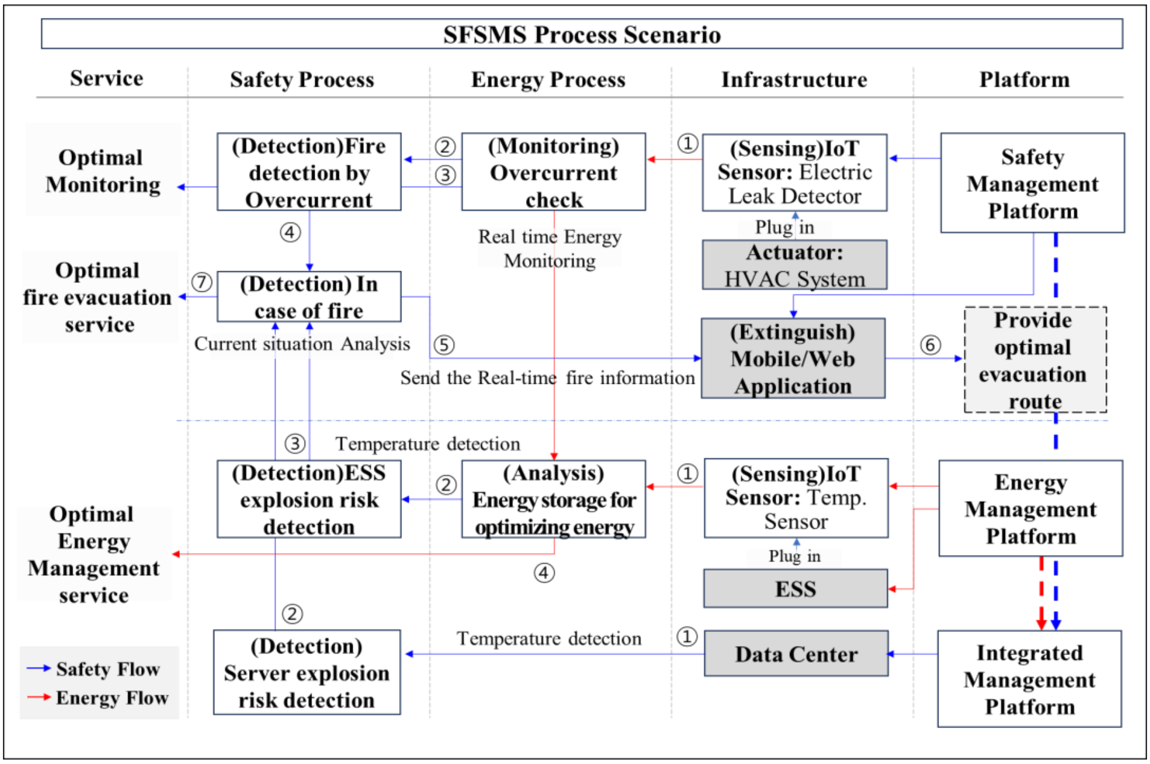


Figure 17. Safety and energy management control process scenario in SFSMS.

7. Analysis of the Result

7.1. SFSMS System Compared to the Existing System

This section demonstrates the novelty of the proposed system by comparing it with an existing system. Table 6 lists the main four points of the proposed systems compared to existing systems. We explain the four points in detail in Sections 7.2 and 7.3.

Table 6. Four differences between existing and proposed systems.

Class	Proposed System	Existing System
Point 1.	- City-based Data Connection by AI Data Center	- Small domain data sharing structure (Building, wildfire management, etc.)
Point 2.	- Sensor—Virtual Edge Gateway (VEG)—cloud server - VEG to occupant's app-based real-time fire data transmission	- Typical network configuration (Sensor to gateway to server) - Sensor to LTE modem to server
Point 3.	- AR-based real-time occupant mobile application - Real-time rescuer/manager web application	- Real-time mobile/web application
Point 4.	- Safety and energy convergence system	- Simple independent domain connection (safety, independent type)

7.2. SFSMS Algorithm Compared to the Existing System

Figure 18 displays the SFSMS algorithms of the existing and proposed systems.

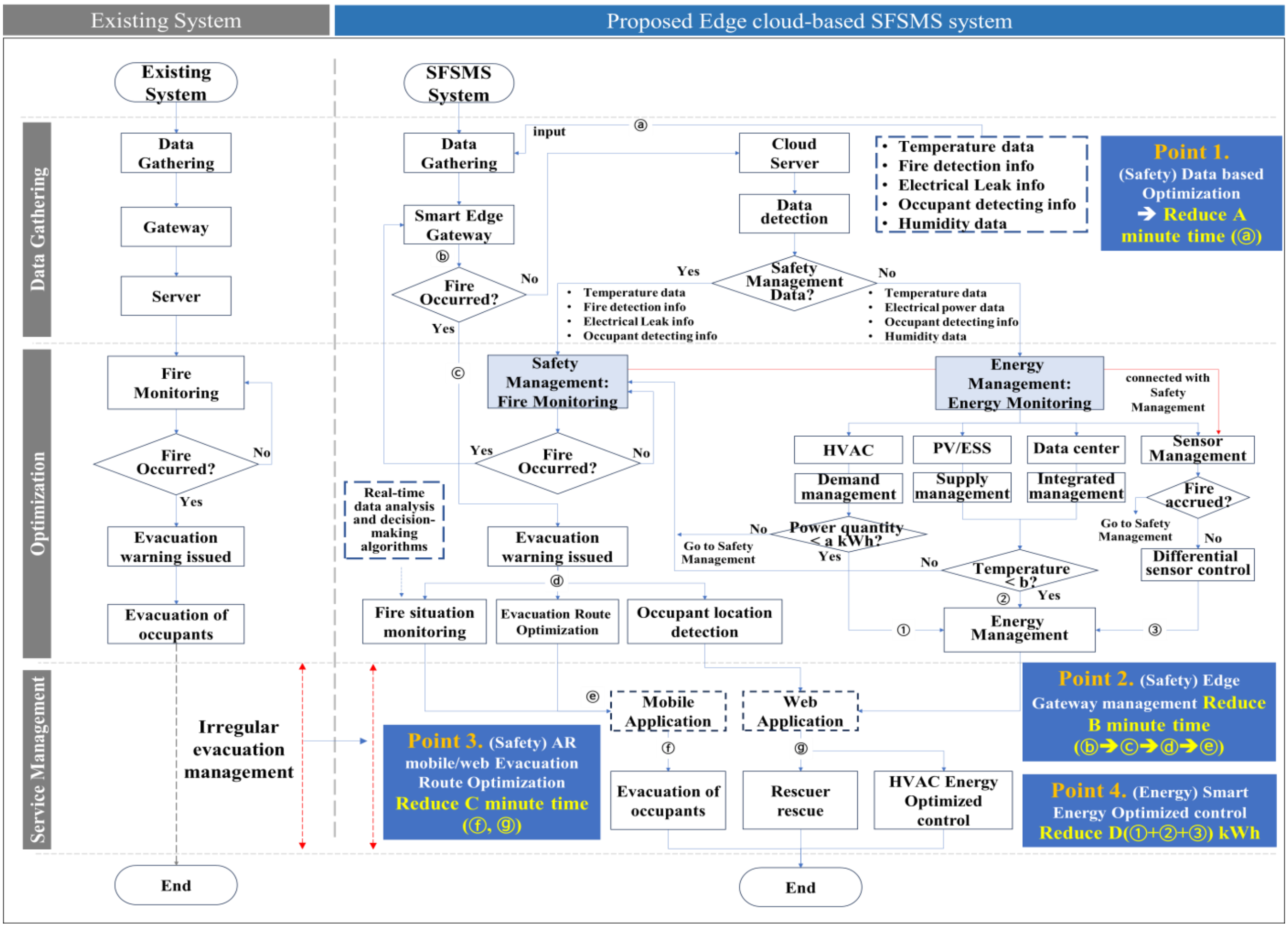


Figure 18. SFSMS algorithm compared to the existing system.

We explain the algorithm in detail in Sections 7.2.1 and 7.2.2. Through this algorithm, we can analyze the following two aspects: optimized evacuation time and energy efficiency. In Section 7.2.3, we describe the four key safety/energy-related points of SFSMS in detail.

7.2.1. Optimized Evacuation Time Analysis

It is important to design a more reasonable avoidance route by introducing real-time data analysis and decision-making algorithms. Moreover, emergency response plans should be strengthened through better evacuation route design. When designing an evacuation route, the reliability of the route must be taken into consideration, as unexpected situations can arise. Many factors affect the speed of evacuation, including the number of people, their age, their speed of movement, and their ability to react. Special groups include people such as children, the elderly, and pregnant women [10]. Additionally, it is important to improve the reliability of software applied to applications. Evacuees can decide whether to follow the route recommended by the system based on their level of trust in the software system. If they have a high level of trust in the system, they will be more likely to follow the recommended route and leave the hazardous area quickly. However, if there are doubts about the reliability of the system, they could either select a path they believe to be safer on their own or even ignore the system's advice, resulting in a double jeopardy situation.

7.2.2. Energy Efficiency Analysis

In this paper, we demonstrate the energy savings in air conditioning systems, ESSs, data centers, and sensor management. This can be observed from the energy management in the algorithm in Figure 18. By comparing the power amounts of the air conditioning system, it can be determined whether to proceed with safety management or energy management. For example, if the amount of power is greater than 1 kWh, it is determined that there is a fire situation and fire management is initiated. In contrast, if it is below 1 kWh, energy management for energy leakage and overcurrent phenomena is progressed. In addition, in the case of ESSs and data centers, safety management is initiated when a fire situation is detected through temperature analysis, and energy management is initiated when the temperature is below this level. Priority-based differential sensor scheduling technology can help to reduce energy consumption by identifying areas with a low risk of fire in advance. For example, in the stand-by stage, the fire detection and temperature detection sensors do not operate simultaneously. Instead, they operate alternately, which can help save energy.

7.2.3. Safety/Energy Four Points for SFSMS

This section presents the following four points for safety management and energy management.

- Point 1: (Safety) digital-based data center integrated management.

The proposed system performs digital-based fire safety management through data collection, enabling efficient and rapid evacuation and rescue. Figure 19 displays the application domain for a data center for smart city applications [40]. The data obtained through the safety and energy systems are stored in an AI-based energy data center and can provide more valuable data-based services based on existing data that have already been established and stored.

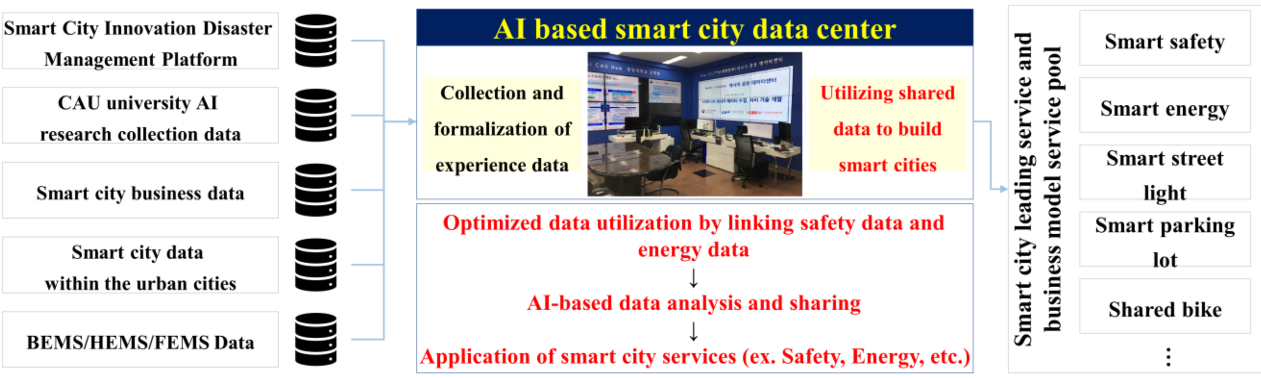


Figure 19. Data-based smart city application domain.

- Point 2: (Safety) Reduce the safety data transfer rates and throughput through the Virtual Edge Gateway. Figure 20 displays a network configuration diagram of the existing and proposed systems for delivering sensor data to the occupants and managers.

The existing system uses LTE-based communication from the gateway to the server, which can cause data transmission delays [31]. The proposed system transmits data to the cloud server in real time through the Virtual Edge Gateway (VEG) internal network depicted in Figure 20 [34]. The VEG uses an internal network as a virtual server. Hence, in the event of a fire, this enables improved data transmission ability through the VEG configuration. The proposed system is divided into two stages: standby and fire. In the standby stage, data are stored on the server similar to the existing system. If in the fire stage, the VEG acts as a virtual server and communicates directly with the user application to quickly transmit fire information. Even if the gateway is destroyed due to a fire, data will be transmitted because it is a virtually connected linkage structure.

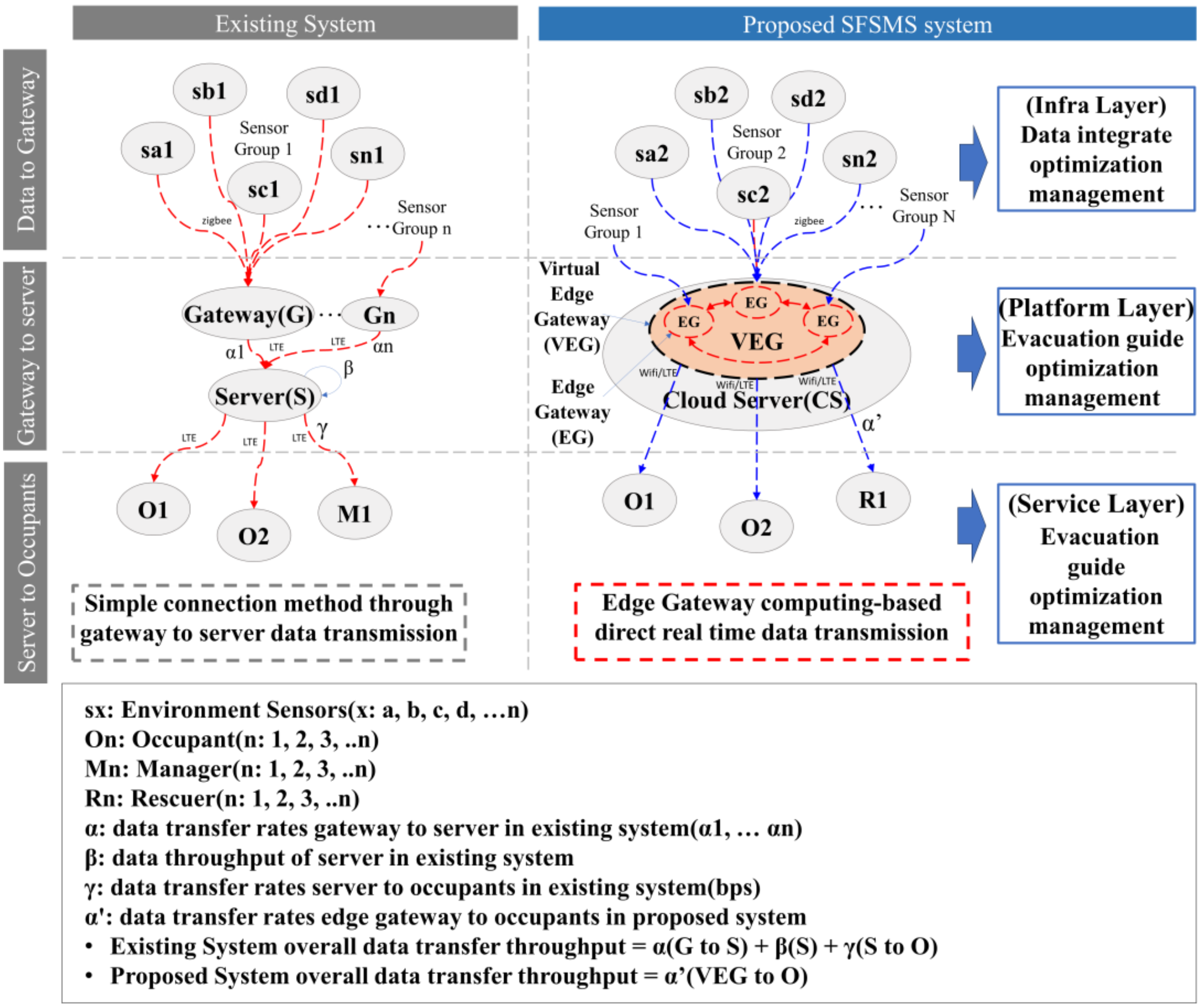


Figure 20. Point 2 for safety management of SFSMS compared to the existing system.

As demonstrated in Figure 20, data are collected from sensors and stored on the server through a gateway in the network structure of the existing system. In this process, the data transmission rate (DTR) of the existing system is described by Equation (1). Here, α is the data transfer rate from the gateway to the server, β is the data throughput of the server in the existing system, and γ is the data transfer rate from the server to the occupants. (G = gateway, S = server, and O = occupant).

$$\text{DTR (existing system)} = \alpha(\text{G to S}) + \beta(\text{S}) + \gamma\ (\text{S to O}) \quad (1)$$

In addition, the network structure of the proposed system is based on VEG, meaning data are directly transmitted from the edge gateway to the occupants. The data transmission rate of the proposed system is described in Equation (2), where α' is the data transfer rate from VEG to the occupants.

$$\text{DTR (proposed SFSMS)} = \alpha'\ (\text{VEG to O}) \quad (2)$$

- Point 3: (Safety) AR mobile/web application for evacuation routing optimization.

In the standby stage, data are transmitted to the cloud server through the gateway because this is the stage before a fire occurs. If a fire occurs and the system is in the fire stage, the fire situation data are transmitted on a cloud basis and quickly shared with occupants and managers through the VEG virtual server. In the existing system, there was no optimized AR-based application for fire management, resulting in irregular evacuation and unstable information exchange in the event of a fire. However, the proposed system is operated by both an AR-based occupant application and a web manager application to manage occupants for efficient evacuation.

- Point 4: (Energy) HVAC, PV, ESS, and sensor management.

As displayed in the energy management part of the algorithm in Figure 18, energy management connected to the safety system consists of HVAC management, ESS, data center, and sensor management. Through HVAC management, when the amount of power is greater than 1 kWh, it detects a fire situation and moves to the safety system. When it is below 1 kWh, a simple energy leak is detected, and energy-saving management is performed. In the case of ESSs and data centers, they are connected to the IoT to check the temperature, prepare for fire situations through temperature detection, and manage safety management to prepare for fire when the temperature is above a certain temperature. Additionally, the sensors provide priority-based fire detection and management with a power-saving architecture. In the stand-by stage, less relevant sensors are sensed while reducing operation time through sensor priority management.

The SFSMS data flow diagram connected with the four points is explained in detail in Section 7.3. The section presents a detailed description of the data flow when transferring data from the sensors to the gateway and the server and when delivering fire information to the occupants.

7.3. SFSMS Data Flow Diagram Compared to the Existing System

In this section, we describe the data flow between the sensors, gateway, cloud server, and mobile/web application compared to the existing system, as presented in Figure 21. The proposed system is divided into stand-by and fire states. In the standby state, data are transferred from the sensor to the gateway and server. Moreover, the cloud server transmits environmental information collected from the sensors to the building manager's web application. This allows the manager to monitor the environmental information (such as safety and energy information) of the building through a web application.

During the fire stage, fire information is transmitted to the cloud server through the edge gateway, and the edge gateway simultaneously transmits real-time PUSH messages (fire situation data) to the occupants' mobile application. The edge gateway functions as a secondary server, providing real-time information directly to the occupants. Additionally, the proposed system achieves high data transmission efficiency by using edge computing-type communication rather than the typical network structure of existing systems. The occupants are then immediately evacuated to avoid fire risks using the AR-based mobile application through high visualization. Unlike the small domain data-sharing structure of the existing system, the proposed system has a city-based data-sharing structure through an AI data center, as depicted in Figure 21, which contains a detailed data flow diagram.

Figure 22 displays the data transmission rate and energy efficiency result graphs of SMSFS. These are the results of the proposed system from points 1 to 4, demonstrating the potential for optimization in terms of system operation time and energy efficiency through the system application. Figure 22a displays the data transmission rate of the proposed system compared to the existing system. This demonstrates that the proposed system has a higher data transmission rate compared to the existing system by using the edge gateway communication, as depicted in Figure 22c. Figure 22b displays the potential for energy savings through smart energy optimization management.

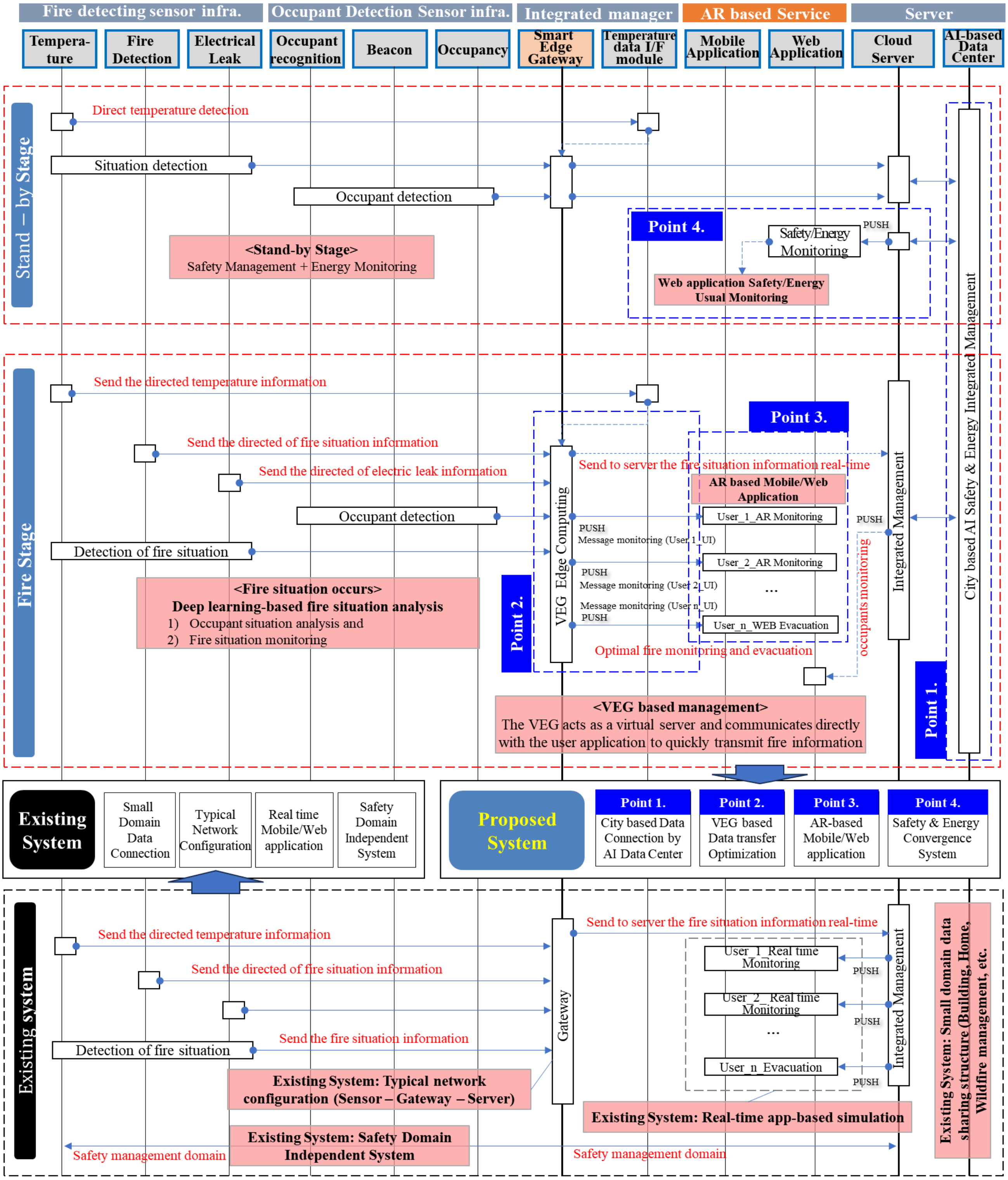


Figure 21. SFSMS data flow diagram compared to the existing system compared to the existing system.

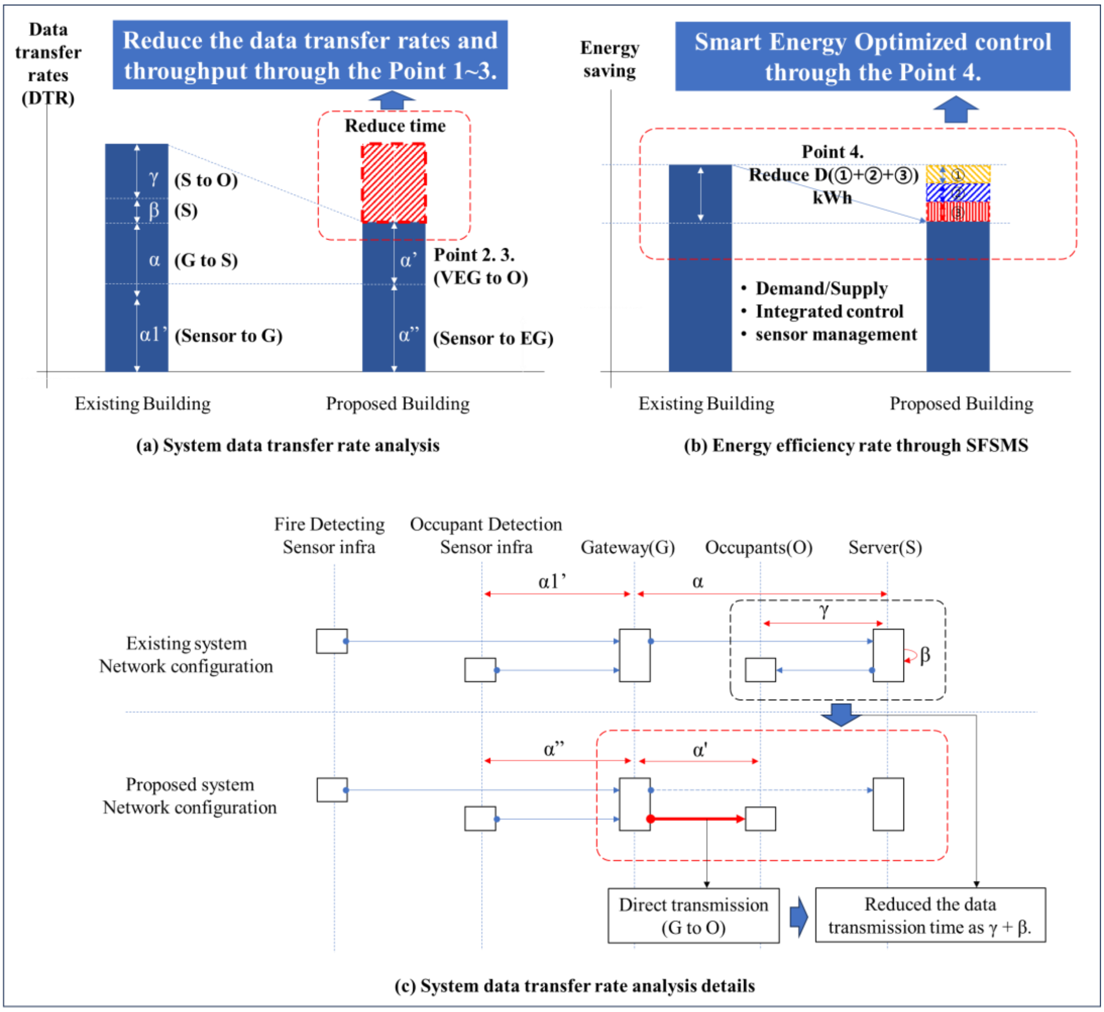


Figure 22. Four points for safety and energy management simulation results.

8. Conclusions

The smart building that manages digital-based fire safety introduced in this paper is very important for optimal data-based management. In our digital society, the need for data-sharing techniques is increasing to the point of enabling AI-based smart city data connections in fields such as buildings, houses, factories, and industrial complexes at the city, governmental, and societal levels. In this paper, we demonstrated the importance of a city-based five-layer safety management architecture that aimed to achieve connectivity between safety and energy data management. Furthermore, we developed a mobile application for occupants and a web application for managers and rescuers, which were applied in the A building in Korea. The final goal of the proposed system was an energy safety system for optimal evacuation and energy efficiency connected to the energy field that could be applied to buildings. We derived four points for optimal evacuation (1 to 3 points) and energy efficiency (4 points) and analyzed the data transmission rate and energy efficiency by comparing them with the existing system. Through this progress, we analyzed the efficiency of the data transfer rate for preventing data communication delays by analyzing the VEG management. Additionally, we were able to provide AI-based services for optimized evacuation through AR-based mobile/web applications. In the future, in terms of the safety and energy fields, we expect to achieve smart buildings that consider fire management and promote a carbon-neutral society by 2030 through research into more accurate data prediction techniques and the development of advanced smart core-related technologies.

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Conflicts of Interest: The authors declare no conflict of interest.

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