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Framework of BIM-Based Quantitative Evaluation for Enhancing Fire Safety Performance of Buildings

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Abstract: The significance of fire inspection has been underscored to prevent building fires, which can lead to property damage and loss of life. While previous studies employed building information modeling (BIM) to evaluate fire safety performance, they primarily focused on a building's physical characteristics, overlooking environmental factors. To address this limitation, we propose a framework of BIM-based quantitative evaluation, which incorporates both physical and environmental characteristics of buildings to enhance their fire safety performance. We conducted a case study featuring three scenarios to validate the proposed framework. The results demonstrate that Scenario 3, with a score of 60.3 points, outperforms Scenarios 1 (30.9 points) and 2 (38.2 points) in terms of fire safety performance. This is attributed to Scenario 3's consideration of components, firefighting equipment, and environmental elements in preventing and responding to building fires. The proposed framework contributes to the field by automatically evaluating buildings' fire safety performance using a comprehensive approach based on BIM. **DOI: 10.1061/JMENEA.MEENG-5709.** © *2023 American Society of Civil Engineers.*

Author keywords: Building information modeling (BIM); Fire safety performance; Quantitative evaluation; Automation; Environmental and physical data.

Introduction

Building fires have caused an increase in the cost of harm to people and property. According to building fire statistics in South Korea, property damage and casualties increased by 92.51% and 17.22%, respectively, from 2017 to 2022 (National Fire Agency 2023c). This increase is due to difficulties in lifesaving and fire suppression operations as a result of the diverse use and complex shape of buildings (Bae and Cha 2023; Hassanain et al. 2017). Accordingly, in many countries various systems to strengthen prevention and response to building fires have been introduced to reduce damage caused by fire. For instance, the US has established fire prevention and response plans at the federal government level based on the Federal Fire Prevention and Control Act and has built fire prevention and response systems for each state and region (US GAO 2022). The UK has enhanced fire safety in buildings after introducing safety certificates for buildings with a height of 18 m or more or 7 stories or more since 2022 (GOV.UK 2022). The South Korean government updates a fire safety master plan every five years to strengthen the infrastructure for building fire safety and is striving to improve its national fire prevention and response system (National Fire Agency 119 2022). Hence, as the examples imply, building fire safety performance evaluation designed to prevent building fires is essential (Omidvari et al. 2015).

To evaluate the fire safety performance of existing buildings, four factors need to be considered (Kironji 2014; Kodur et al. 2020; Silvani and Morandini 2009; Zhou et al. 2021). The first factor is to check if firefighting equipment (e.g., fire alarm system, fire suppression equipment, emergency egress routes) is properly installed in the building. However, subjective judgment may be involved because firefighting equipment is installed by people (owner, operator, architectural engineer, etc.). Accordingly, evaluation results may vary depending on the inspector's experience, and errors or omissions are likely to occur. De Filippo et al. (2023) evaluated various defects (crack, delamination, leakage, etc.) in concrete structures, including concrete spalling failure caused by fire, using drones and artificial intelligence (AI).

The second factor is to evaluate structural safety by considering a building's durability, fire resistance, and heat resistance. However, when a building's structural condition is evaluated, it is difficult for the inspector to enter a narrow space directly, and there is a high risk of unexpected accidents. Also, it is very time-consuming because the inspector has to go around the building to evaluate the architectural structure. Razafimahazo et al. (2021) developed an indoor inspection drone for evaluating buildings' health and fire protection systems. The drone's performance is optimized to move in a limited space.

The third factor is to perform the fire simulation based on the virtual building model. The simulation allows the fire propagation path to be analyzed to establish evacuation and firefighting action plans. However, since it predicts risks and evacuation routes in the

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event of a fire, its prediction may be different from actual outcomes. This is because the assumptions and variables entered into the simulation model may differ from the actual ones. Song et al. (2019) proposed a spatial data model to predict the propagation path of heat and smoke generated in a fire. The model contains spatial, semantic, and topological data that can be used for building fire simulation and analysis. The fourth factor is to measure the reaction of various elements of the building (e.g., materials, structures) due to fire. However, since the fire experiment evaluates performance when there is a fire in a real building or a virtual model, safety-related accidents may occur, and the cost of the experiment is relatively high. Fu (2020) used machine learning to evaluate the possibility of progressive collapse caused by fires in steel-framed buildings. The training data were established by Monte Carlo simulation and random sampling. Studies that evaluate building performance based on advanced technologies (drones, AI, etc.) have been developed to solve the limitations of general methods. However, they do not consider all elements (e.g., firefighting equipment, structure, etc.). Thus, studies using building information modeling (BIM) have been conducted.

BIM, which has the physical and functional characteristics of various objects (e.g., wall, door, window) as digital data, can represent the attributes of a building (material, cost, etc.) as a three-dimensional (3D) digital model (Gan 2022; Koo and O'Connor 2022; Shahi et al. 2019; da Silva et al. 2022). Current BIM integrates building information based on a virtual 3D digital model, thus allowing various stakeholders to manage and share data produced during the building's life cycle (Yang et al. 2021). Accordingly, the BIM model that contains various attribute information (i.e., material, cost) can be utilized for simulation or evaluation (da Silva et al. 2022). Specifically, the BIM model can analyze and manage building fire safety performance by integrating information such as building structure and facility (Chen et al. 2021; Sun and Turkan 2020). As this model is continuously updated to reflect changes in structure, materials, and other aspects during the building's maintenance phase, it provides a consistent and accurate foundation for ongoing fire safety management (Abdirad 2022; Wang and Meng 2021). This implies that any changes that affect fire safety performance can be quickly addressed through the BIM model. Furthermore, the BIM model enables predictive modeling of potential fire scenarios, assisting in proactive fire safety management. With its 3D visualization capabilities, it provides a way to identify potential vulnerabilities before a fire occurs (Go et al. 2022; Tayeh and Issa 2020).

Previous studies regarding building fire safety performance considered various factors (firefighting equipment, structure, etc.) based on the BIM model. Zhang (2020) developed a fire risk assessment system using a BIM model that considers various factors (i.e., structural integrity, number of entry and exit points, fire alarm and detection systems, and firefighting equipment) that can affect fire occurrence, spread, occupant safety, and the like. Wang et al. (2015) proposed a BIM model consisting of four modules (evacuation assessment, escape route planning, safety education, and equipment maintenance) to support building fire safety management. Zhang et al. (2019) developed a prototype model to inspect several aspects (outdoor premises, electrical systems, fire extinguishers, etc.) related to building fire safety based on collective intelligence and BIM-based virtual reality. As such, many considerations (e.g., firefighting equipment, structure) were integrated in previous research on the evaluation of fire safety performance using BIM. However, this research only considered the physical elements (structure, material, firefighting equipment, etc.) of a building and did not include environmental elements (e.g., region, occupant).

Environmental elements can affect fire suppression operations or rescue and evacuation of occupants. Accordingly, when an evacuation strategy is established, it is necessary to know the time needed for safe evacuation for all occupants (Rahardjo and Prihanton 2020). However, the selection of an evacuation route is influenced by the environment surrounding the building, and the evacuation time may vary depending on the structure type. Also, the distance from the building to the fire service agency and access routes for emergency vehicles affect rescue. Performance evaluation should therefore include environmental elements that affect fire response. Accordingly, this study seeks to develop a framework capable of quantitatively evaluating building fire safety performance, including environmental and physical elements of existing buildings.

Quantitative Evaluation Framework

Fig. 1 shows the quantitative framework for evaluating building fire safety performance. First, a database, quantitative evaluation elements, criteria, and formulas were established to evaluate the fire safety of a building. Second, a dynamo-based evaluation algorithm was developed to perform evaluation automatically. Third, the BIM model containing physical and environmental data was generated from the 2D drawing of an existing building. Fourth, based on established elements, criteria, and formulas, a dynamo-based evaluation algorithm was developed. Finally, the effectiveness of the proposed framework was verified by performing fire safety performance evaluation according to one of three scenarios using the evaluation algorithm.

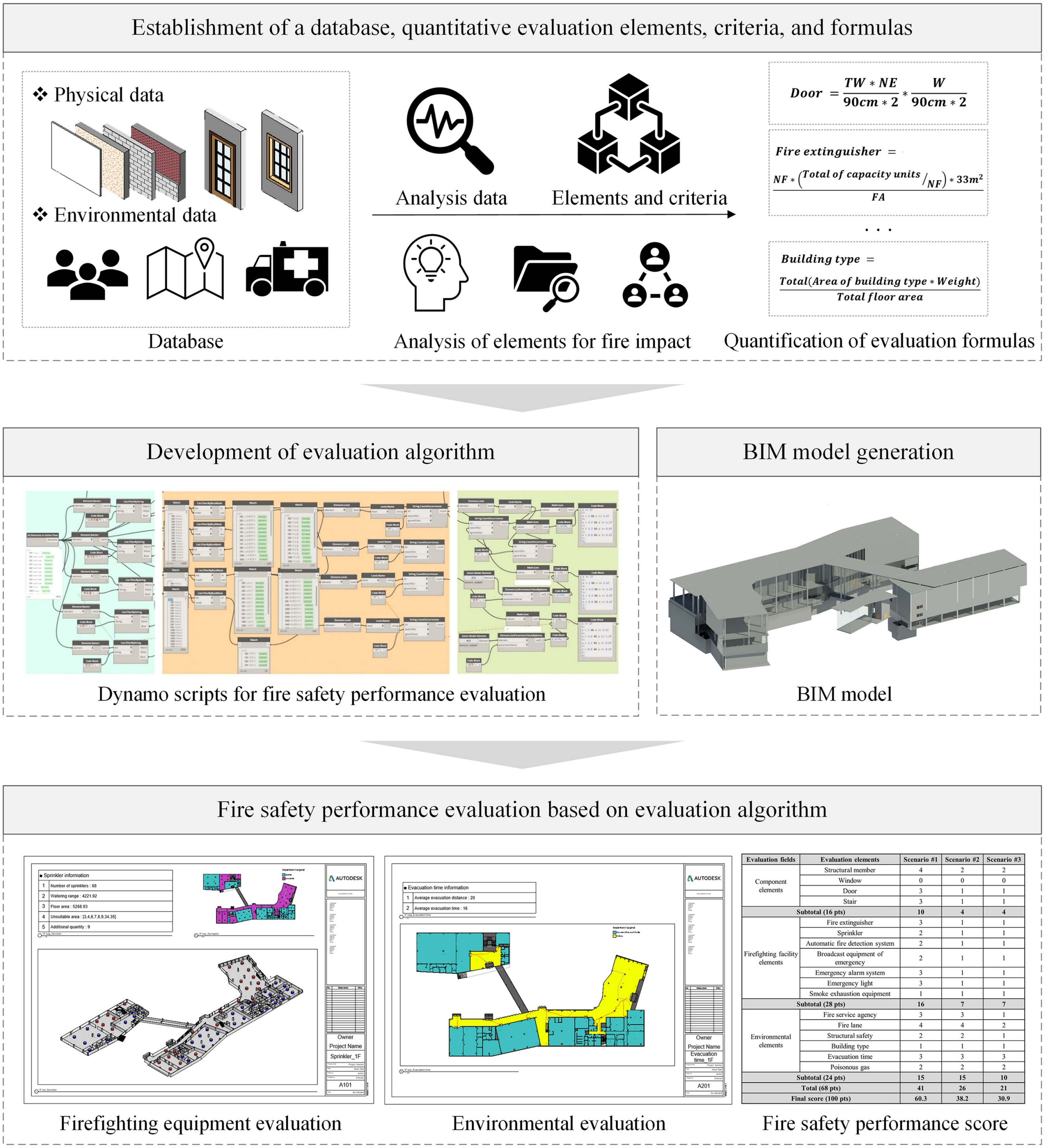
Three scenarios for the target building were established. The "S" cultural and assembly facility designed with building fire safety taken into account was used as a case study. This building, designed for fire safety education and experience programs, was constructed with a total floor area of 21,116 m^2. It is operated directly by firefighters whose expertise contributes to the creation of a highly secure and fire-safe environment within the facility. The building achieved a Grade-A performance rating (National Fire Agency 2023a). The three scenarios for building fire safety conditions are as follows.

In Scenario 1, among various elements that evaluate building fire safety performance, problems occur in physical characteristics (i.e., building components and firefighting equipment elements) and environmental characteristics (i.e., environmental elements). In Scenario 2 problems occur only in building components and firefighting equipment elements with physical characteristics. In Scenario 3, performance is reflected and rated excellent in terms of physical and environmental characteristics. The five large fire accidents in South Korea are as follows: "M"—mixed-use building (casualties: 58; fire damage cost: US$6,984,435); "J"—indoor sports arena (casualties: 66; fire damage cost: US$1,619,304); "S"—medical facility (casualties: 189; fire damage cost: US$351,747); "S"—office building (casualties: 15; fire damage cost: US$175,112); and "J"—apartment building (casualties: 18; fire damage cost: US$45,414). Problems that are present in the physical or environmental characteristics applied to Scenarios 1 and 2 were established (National Fire Agency 2023c).

Proposed Framework Validation

Database

To solve the limitation of previous building fire safety performance evaluation using BIM, this study intends to evaluate building fire



$$Door = \frac{TW * NE}{90cm * 2} * \frac{W}{90cm * 2}$$

$$Fire\ extinguisher = \frac{NF * \left({}^{Total\ of\ capacity\ units}/_{NF}\right) * 33m^2}{FA}$$

. . .

$$Building\ type = \frac{Total(Area\ of\ building\ type * Weight)}{Total\ floor\ area}$$

■ Sprinkler information
1 Number of sprinklers : 68
2 Watering range : 4221.92
3 Floor area : 5268.93
4 Unsuitable area : [3,4,6,7,8,9,34,35]
5 Additional quantity : 9

■ Evacuation time information
1 Average evacuation distance : 20
2 Average evacuation time : 16

Evaluation fields	Evaluation elements	Scenario #1	Scenario #2	Scenario #3
Component elements	Structural member	4	2	2
	Window	0	0	0
	Door	3	1	1
	Stair	3	1	1
Subtotal (16 pts)		10	4	4
Firefighting facility elements	Fire extinguisher	3	1	1
	Sprinkler	2	1	1
	Automatic fire detection system	2	1	1
	Broadcast equipment of emergency	2	1	1
	Emergency alarm system	3	1	1
	Emergency light	3	1	1
	Smoke exhaustion equipment	1	1	1
Subtotal (28 pts)		16	7	7
Environmental elements	Fire service agency	3	3	1
	Fire lane	4	4	2
	Structural safety	2	2	1
	Building type	1	1	1
	Evacuation time	3	3	3
	Poisonous gas	2	2	2
Subtotal (24 pts)		15	15	10
Total (68 pts)		41	26	21
Final score (100 pts)		60.3	38.2	30.9

Fig. 1. Framework for quantitative performance evaluation.

safety performance for elements with physical characteristics (i.e., building component elements and firefighting equipment element) and environmental characteristics (i.e., environmental elements).

Physical Data

Identifying and understanding the risk factors inherent in the building in advance (Meacham et al. 2016) can help reduce the damage caused by fire (Meacham et al. 2016). The BIM model created based on a building's physical objects (wall, door, window, etc.) can be used to evaluate the direct effects of heat and smoke caused by fire. Hence, performance can be improved by removing or mitigating the inherent risk factors before a fire occurs using The BIM model. However, the BIM model has limitations. Accordingly, this study attempts to define the BIM model evaluation element and element information for evaluating performance considering only the objects that affect fire safety.

Among the objects with physical characteristics, the elements that should be considered can be divided into two categories (building component elements and firefighting equipment elements).

First, the building components form the shape and structure of a building and include walls, floors, ceilings, windows, and doors. These play a key role in limiting or preventing the transfer of flame and heat in the event of a fire and affect the rescue of occupants (Avlar et al. 2022; Lee and Lee 2013). For example, the wall prevents flames from spreading to adjacent rooms and reduces heat transfer. Doors and windows facilitate evacuation and can serve as entrances for a fire rescue operations Firefighting equipment elements prevent the spread of smoke caused by fire and secure clear visibility (Garcia-Martin et al. 2019; González-Briones et al. 2020; Tongthong et al. 2023). However, if these are not correctly installed, or they fail to function properly, fire safety can be reduced. Thus, the firefighting equipment elements, such as the air-conditioning, lighting, and sanitation systems, are essential for fire suppression and lifesaving operations. Accordingly, this study evaluates the fire safety performance of components and firefighting equipment among objects with physical characteristics. The element-specific information (e.g., fire extinguishing capability, sprinkler coverage) was collected from the Fire Safety Shopping Mall operated by the Korea Fire Protection Authority (KFPA 2023).

Environmental Data

Not only component elements and firefighting equipment elements with physical characteristics but also environmental elements should be taken into account. Environmental elements hold information that can evaluate various fire effects depending on the current state and environment of the building. The authors collected three types of data (occupants, surrounding environment, and hazardous materials). First, it is important to have fire evacuation routes and time to ensure the life and safety of occupants in a building. Thus, the characteristics of occupants (age, physical characteristics, gender, etc.) act as important variables in determining evacuation route and time (Lin et al. 2020). The authors collected this information from Healthline, which provides medical expertise based on the experience of more than 150 medical professionals (Bohannon 1997; Healthline 2023).

Second, the surrounding environment (e.g., region, climate, infrastructure), according to the location of the building, significantly impacts the ability to respond to fire. For example, there is a difference in fire extinguishing time and property damage between easy and difficult access to the location of a fire. According to the National Fire Data System of South Korea, the effect of early fire extinguishing amounts to US$4,748,459,000. This suggests that if firefighters quickly arrive at the scene of a fire, damage can be reduced by more than 53 times (National Fire Agency 2023c). Therefore, information about the surrounding environment was collected from the Public Data portal operated by the Ministry of the Interior and Safety (2023).

Third, a hazardous material is a substance that may cause a disaster or an accident, such as fire, explosion, or poisoning. Hazardous materials increase the risk of fire because they generate explosions and toxic gases. Accordingly, it is necessary to evaluate a fire hazard according to the amount, grade, and toxication concentration of a hazardous material. In this study, information on hazardous materials was collected from the National Dangerous Goods Information System (National Fire Agency 2023b).

Quantitative Evaluation Elements, Criteria, and Formulas

Evaluation Elements and Criteria

To quantitatively evaluate fire safety performance, the evaluation fields were divided into three elements (component element, firefighting element, and environmental element), and the evaluation criteria were established for each one. The evaluation elements and criteria were defined based on Korean building fire safety standards (National Law Information Center 2017, 2023; Table 1). First, the building component and firefighting equipment elements are composed of four evaluation elements (structural member, door, window, and stair) and seven evaluation elements (fire extinguisher, sprinkler, automatic fire detection system, emergency broadcast equipment, emergency alarm system, emergency light, and smoke exhaustion equipment). Also, the environmental elements consist of six elements (fire service agency, fire lane, structural safety, building type, evacuation time, and poisonous gas).

Second, evaluation criteria (e.g., fire resistance performance, fire extinguishing performance, effective rescue range) for assessing performance based on attribute information (fire extinguishing capacity, alarm coverage, etc.) are defined. For example, structural members in the component element cause a difference in delay time for cracks and building collapse depending on fire resistance performance. Structural steel maintains only about 50% of its ambient temperature strength at 550°C–600°C. Steel with higher thermal

Table 1. Performance evaluation elements and criteria

Field	Element	Criteria
Building component elements	Structural member	Fire resistance
	Door	Entrance
	Window	Window
	Stair	Stair dimensions
Firefighting equipment elements	Fire extinguisher	Firefighting capability per 33 m^2 of floor area
	Sprinkler	Effective sprinkler coverage per unit area
	Automatic fire detection system	Coverage per unit area
	Emergency broadcast equipment	Coverage per unit area
	Emergency alarm system	Coverage per unit area
	Emergency light	Coverage per unit area
	Smoke exhaustion equipment	Natural ventilation area per 100 m^2 of floor area
Environmental elements	Fire service agency	Number of fire stations in area
	Fire lane	Number and effective width of access roads
	Structural safety	Expansion area and age of building
	Building type	Fire risk by type
	Evacuation time	According to building structure
	Poisonous gas	According to area of finishing materials

conductivity can heat up rapidly in the event of a fire and thus increase fire damage (Lucherini and Maluk 2019). On the other hand, since concrete has high durability as an incombustible material, it can withstand high temperatures and reduce the spread of fire. Accordingly, fire resistance performance was determined as a criterion for evaluation of the structural member. Also, the specifications and performance of the doors, windows, and stairs lead to a difference in connectivity between the interior and exterior spaces of the building. This difference can affect evacuation and rescue activities due to a building fire. For example, depending on the fire resistance rating of a door, there is a difference in the amount of time to block the heat caused by the fire (e.g., 20 min, 30 min, ¾ 1/2 h, 1 h, 1-1/2 h, and 3 h) (Havel 2013). Also, gaps between the door and the door frame can be a passageway for smoke from a fire. Standards were set for gaps around the top, side, and bottom of doors (top and side: 3–4 mm; bottom: 10 mm) to reduce the spread of smoke (Huziej 2022). Namely, there is a difference in escape time depending on the resistance rating by door type.

Evaluation Formulas and Weighting Factors

Formulas for objectively evaluating building fire safety performance were established, considering specific evaluation criteria based on fire laws and regulations in South Korea (National Law Information Center 2017, 2023). As shown in Eqs. (1)–(16), performance evaluation can be based on diverse building information (material, shape, region, user, etc.). Among the formulas for the 16 evaluation elements, 3 formulas are to be explained as examples. First, in the case of the stair, which belongs to the component element, its width, height, and depth are divided by the effective value of the installation standard (i.e., 120, 16, 26 cm) to obtain the averages, and then the sum of the averages is divided by the number of stairs to calculate the result [Eq. (3)]. This indicates that the closer the width, height, and depth are to the installation standards, and the fewer the stairs, the higher the score. For example, the score for a stair with an effective width of 1,000 mm, a height of 204 mm, and a width of 300 mm is calculated at 3.26 points. Second, the score for the sprinkler, a firefighting equipment element, is calculated using the number of sprinklers installed, effective fire suppression capability, fire extinguisher installation area (i.e., 33 m^2), and floor area [Eq. (4)]. This indicates that a higher evaluation score is achievable when there is a higher number of sprinklers, higher fire suppression capability, and a smaller floor area. For example, if there are 25 fire extinguishers, the effective fire suppression capability is 1 and the floor area is 1,613.83 m^2; hence, the value for the sprinkler is calculated at 0.51 points.

Third, the evaluation score for the fire service agency, which belongs to the environmental element, is calculated by adding the number of fire stations, emergency call (119) centers, and rescue teams in the area where the building is located, and dividing the sum by the area of each location [Eq. (11)]. This means that a higher evaluation score can be obtained when there are many of these elements and the area of each location is smaller. For example, if there are 16 fire stations, 69 119 centers, and 16 rescue teams, and the area of the location is 20,569 km^2, the score for the fire service agency is calculated at 0.00491 points.

The following are the formulas used in the study:

$$\text{BFSP}_{\text{door}} = \frac{TW \times NE}{90\ \text{cm} \times 2} \times \frac{W}{90\ \text{cm} \times 2} \tag{1}$$

where $\text{BFSP}_{\text{door}}$ = performance for the door; TW = total width of doors; NE = number of entrances; and W = sum of weights

$$\text{BFSP}_{\text{window}} = \frac{WA \times W \times 20}{FA \times NW} \tag{2}$$

where $\text{BFSP}_{\text{window}}$ = performance for the window; W = sum of the weights; WA = window area; FA = floor area; and NW = number of windows

$$\text{BFSP}_{\text{stair}} = \frac{\text{Total}\left(\frac{\frac{w}{120\ \text{cm}} + \frac{h}{16\ \text{cm}} + \frac{d}{26\ \text{cm}}}{3}\right)}{NS} \tag{3}$$

where $\text{BFSP}_{\text{stair}}$ = performance for the stair; NS = number of stairs; w = width of stair; h = height of the stair; and d = depth of stair

$$\text{BFSP}_{\text{fire extinguisher}} = \frac{NF \times \left(\frac{\text{Total capacity units}}{NF}\right) \times 33\ \text{m}^2}{FA} \tag{4}$$

where $\text{BFSP}_{\text{fire extinguisher}}$ = performance for the fire extinguisher; NF = number of fire extinguishers; and FA = floor area

$$\text{BFSP}_{\text{sprinkler}} = \frac{NS \times \left(\frac{\text{TAC}}{NS}\right)}{FA} \tag{5}$$

where $\text{BFSP}_{\text{sprinkler}}$ = performance for the sprinkler; NS = number of sprinklers; TAC = total area of coverage; and FA = floor area

$$\text{BFSP}_{\text{automatic fire detection system}} = \frac{ND \times \left(\frac{\text{TAC}}{ND}\right)}{FA} \tag{6}$$

where $\text{BFSP}_{\text{automatic fire detection system}}$ = performance for the automatic fire detection system; FA = floor area; TAC = total area of coverage; and ND = number of automatic fire detection systems

$$\text{BFSP}_{\text{emergency broadcast equipment}} = \frac{NB \times \left(\frac{\text{TAC}}{NB}\right)}{FA} \tag{7}$$

where $\text{BFSP}_{\text{emergency broadcast equipment}}$ = performance for the broadcast equipment of the emergency; FA = floor area; TAC = total area of coverage; and NB = number of broadcast equipment of emergency

$$\text{BFSP}_{\text{emergency alarm system}} = \frac{NA \times \left(\frac{\text{TAC}}{NA}\right)}{FA} \tag{8}$$

where $\text{BFSP}_{\text{emergency alarm system}}$ = performance for the emergency alarm system; FA = floor area; TAC = total area of coverage; and NA = number of emergency alarm systems

$$\text{BFSP}_{\text{emergency light}} = \frac{NL\left(\frac{\text{Total lux}}{NL}\right)}{FA} \tag{9}$$

where $\text{BFSP}_{\text{emergency light}}$ = performance for the emergency light; FA = floor area, and NL = number of emergency lights

$$\text{BFSP}_{\text{smoke exhaustion equipment}} = \frac{\text{Total } VWA \times 100}{FA} \tag{10}$$

where $\text{BFSP}_{\text{smoke exhaustion equipment}}$ = performance for the smoke exhaustion equipment; FA = floor area; and VWA = ventilation window area

$$\text{BFSP}_{\text{fire service agency}} = \frac{NS + NC + NR}{\text{Area of region}} \tag{11}$$

where $\text{BFSP}_{\text{fire service agency}}$ = performance for the fire service agency; NS = number of fire stations; NC = number of 119 call centers; and NR = number of rescues teams

$$\text{BFSP}_{\text{firelane}} = WR \times NR \tag{12}$$

where $\mathrm{BFSP}_{\mathrm{firelane}}$ = performance for the fire lane; WR = width of adjacent roads; and NR = number of access roads

$$\mathrm{BFSP}_{\text{structural safety}} = \frac{EA \times \text{Weight}}{\text{Total of } FA} \tag{13}$$

where $\mathrm{BFSP}_{\text{structural safety}}$ = performance for structural safety; EA = expanded area; and FA = floor area

$$\mathrm{BFSP}_{\text{building type}} = \frac{\text{Total}\,(\mathrm{ABT} \times \text{Weight})}{\text{Total } FA} \tag{14}$$

where $\mathrm{BFSP}_{\text{building type}}$ = performance for the building type; ABT = area of building type; and FA = floor area

$$\mathrm{BFSP}_{\text{evacuation time}} = \frac{\mathrm{PWS} \times ED}{\text{Average walking speed by evacuation distance}} \tag{15}$$

where $\mathrm{BFSP}_{\text{evacuation time}}$ = performance for the evacuation time; PWS = pedestrian walking speed by age group; ED = evacuation distance; and AWS = average walking speed by evacuation distance

$$\mathrm{BFSP}_{\text{poisonous gas}} = \frac{A \times TI}{\text{Total } A \times 0.867} \tag{16}$$

where $\mathrm{BFSP}_{\text{poisonous gas}}$ = performance for the poisonous gas; A = area by type of finishing material; and TI = toxicity index by type of finishing material.

Evaluation formulas for each element were set, and the weighting factor was applied to calculate the evaluation result. According to the results of extensive interviews with building fire safety experts at the National Fire Agency in South Korea, weights were applied according to the importance of specific elements—door, window, structural safety, and building type—that can cause additional damage in the event of a fire. First, as the fire resistance rating of the door increases, additional damage is less likely. The fire resistance rating is an index that indicates how long a door withstands fire; a higher rating means the door withstands fire longer (Kim et al. 2020). Second, since the degree of fire spread varies depending on the window layout (i.e., I-type, L-type, and C-type), the scale of damage also varies (Cicione et al. 2019; Kolbrecki 2015). For example, the fire is likely to spread quickly to the upper floors in the I-type layout while it is likely to spread to the room adjacent to the one with the L-type layout. The C-type is a layout in which the window is added to the L-type and can increase fire damage further than the L-type. Third, as the building ages and its durability decreases, its ability to cope with fire is reduced (Lee et al. 2021; Salleh et al. 2023). Fourth, as the machinery and equipment installed inside the building differ depending on the building type, the damage may vary. As a result, the weighting factor was set to increase the evaluation by 10% considering the fire damage increased by the four evaluation elements (Table 2).

The values calculated using the evaluation formula vary depending on the element. They should therefore be normalized to evaluate all elements with the same importance level without being biased toward the evaluation results for a specific element. In this study, normalization was performed using a linear interpolation method to estimate the value based on a linear polynomial between any two known values (Noor et al. 2015). As shown in Table 3, the evaluation scores for 17 elements were normalized to 0 to 4 points. First, a normalized value was set according to the building's main structural materials (e.g., reinforced concrete, stone, brick, etc.) for the structural member. For example, reinforced concrete outperforms steel and wood in terms of mechanical properties at high temperatures (Qin et al. 2022). On the other hand, in a panel containing flammable core insulation (Styrofoam, polyurethane, etc.) flame propagates more easily than in stone or brick. For this reason, the highest score of four points was set for the reinforced concrete, whereas the lowest point of 0 was given to the panel. Second, the evaluation scores for the remaining elements were normalized based on the linear polynomial estimated with the values when performance was superior (maximum value) and inferior (minimum value).

Evaluation Algorithm

Based on established elements, criteria, and formulas, a dynamo-based evaluation algorithm was developed to evaluate building fire safety performance. As shown in Fig. 2, the algorithm developed in this study consists of three steps.

Step 1 (importing data for evaluation): data corresponding to the evaluation elements are extracted from all data in the BIM model imported to the dynamo. The evaluation data extracted from the BIM model are divided into building component, firefighting equipment, and environmental. For example, doors, fire extinguishers, and building types are classified as component elements, firefighting equipment elements, and environmental elements, respectively.

Table 2. Weighing factors

Field	Element	Weighting criteria	Type	Weighting factor
Building component elements	Door	Fire resistance rating	A-rated	1.2
			B-rated	1.1
			General	1.0
	Window	Layout	I-type	1.2
			L-type	1.1
			C-type	1.0
Environmental elements	Structural safety	Age of building	30 years	1.0
			22.5–30 years	1.1
			15–22.5 years	1.2
			7.5–15 years	1.3
			~7.5 years	1.4
	Building type	Fire resistance performance according to building use	Tourist facilities, elderly facilities	1.3
			Residential, community living, medical, fitness, education	1.2
			Training, business, cultural gathering	1.1
			Accommodation, religious, sales, multiuse	1.0

Table 3. Normalized values by evaluation element

Field	Element	Normalized values				
		4	3	2	1	0
Component elements	Structural member	Reinforced(steel) concrete	—	Plain concrete, stone, brick	Steel frame construction	Panel, wooden construction
	Window Door Stair	More than 2	Less than 2–more than 1.5	Less than 1.5–more than 1	Less than 1–more than 0.5	Less than 0.5
Firefighting equipment elements	Fire extinguisher Sprinkler Automatic fire detection system Emergency broadcast equipment Emergency alarm system Emergency light Smoke exhaustion equipment	More than 2	Less than 2–more than 1.5	Less than 1.5–more than 1	Less than 1–more than 0.5	Less than 0.5
Environmental elements	Fire service agency Fire lane Structural safety Building type Evacuation time Poisonous gas	More than 2	Less than 2–More than 1.5	Less than 1.5–More than 1	Less than 1–More than 0.5	Less than 0.5

Step 2 (calculating scores using evaluation formulas): based on the evaluation formulas [Eqs. (1)–(16)], performance of the elements classified in Step 1 is calculated. For example, door, fire extinguisher, and building type are calculated using Eqs. (1), (4), and (14), respectively.

Step 3 (extracting evaluation results): the result for each element is normalized to 0–4 points through linear interpolation. Performance is evaluated by aggregating the normalized values for each element. The results are exported to a spreadsheet.

BIM Model Generation

The BIM model should include the information needed to evaluate building fire safety performance. Toward this end, the model was generated with two types of data (i.e., physical and environmental) using Revit software (Fig. 3). The elements (e.g., wall, floor, ceiling, etc.) that constitute the building among the physical data were created based on a two-dimensional (2D) drawing, which included information on area, number of floors, and number of rooms. The firefighting equipment included six evaluation elements (fire extinguisher, sprinkler, automatic fire detection system, emergency broadcast equipment, emergency alarm system, emergency light, and smoke exhaustion). Additionally included was attribute information such as material, fire extinguishing capability, and alarm coverage. Lastly, environmental data (e.g., fire service agency, building type, etc.) was included in the model.

Evaluation Algorithm Results

Table 4 shows the performance evaluation results for the three scenarios based on the 'S' cultural and assembly facility. Therefore, the validity of the present research is verified by checking the results according to the three scenarios. Scenario 1 had the lowest score (30.90 points). When compared with Scenario 2, the scores for the building component element (4 points) and the firefighting equipment element (7 points) were the same, but the scores for the environment element differed by 5 points. Thus for Scenario 1 to achieve the same safety performance as Scenario 2, enhancements would be required in the environment, including fire lanes and incombustible materials. Moreover, not only physical but also environmental elements have an impact on performance. Second, when compared with Scenario 1's 30.9 points and Scenario 2's 38.2 points, Scenario 3's 60.3 points had the best performance. This is because it reflected the excellent fire safety performance of the S cultural and assembly facility. However, despite regular inspections and compliance with fire safety standards, the building did not reach the maximum score of 100 points. This indicates that even buildings with excellent fire safety performance may not meet the evaluation criteria defined in this study, which are more detailed in terms of performance, identifying areas of improvement that may not have been identified using traditional fire safety performance evaluation methods. Then, compared with Scenario 3 (building component element: 10 points; firefighting equipment element: 16 points), Scenario 2 (building component element: 4 points; firefighting equipment element: 7 points) was found to have unsatisfactory (low) performance in building component and firefighting equipment elements. For Scenario 2 to achieve the same fire safety performance as Scenario 3, it would be necessary to enhance the performance of building component elements and improve the fire safety measures of physical elements. This might involve the installation of additional fire extinguishers and sprinklers.

Conclusions

Because building fires cause harm to people and properties, the importance of fire inspection is highlighted. Here, BIM is recommended because it collects and stores physical data (structure, material, etc.) and evaluates performance. However, previous studies may have considered a building's physical characteristics, but they failed to consider its environmental characteristics, which play a significant role in building fire safety. Hence, proposed here is a quantitative evaluation framework to improve building fire safety performance based on BIM. To verify the proposed framework, a case study for three scenarios was conducted. The three scenarios considered both physical and environmental problems.

The evaluation fields (building component elements, firefighting equipment elements, and environmental elements), evaluation elements (structural member, door, and window), and evaluation

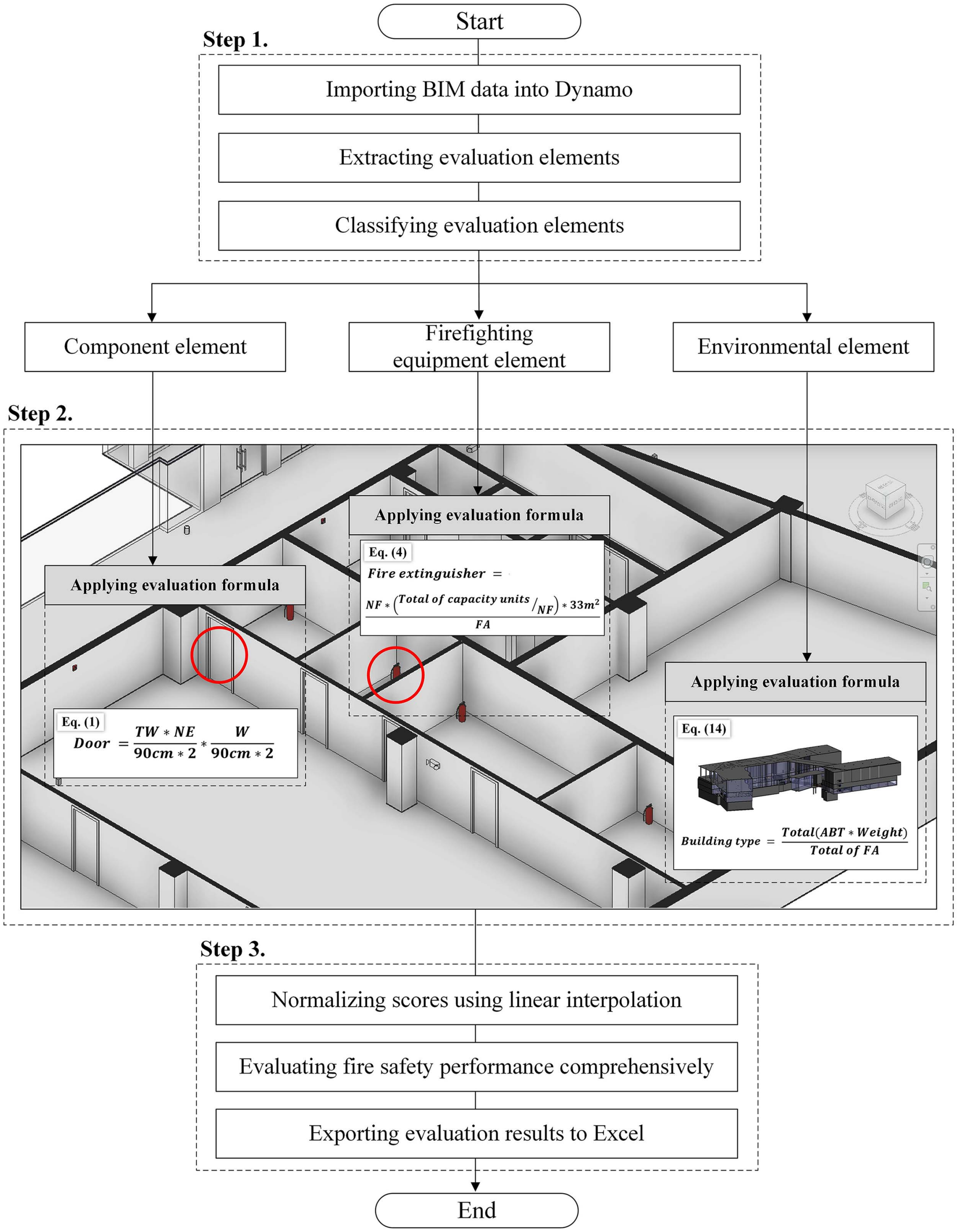
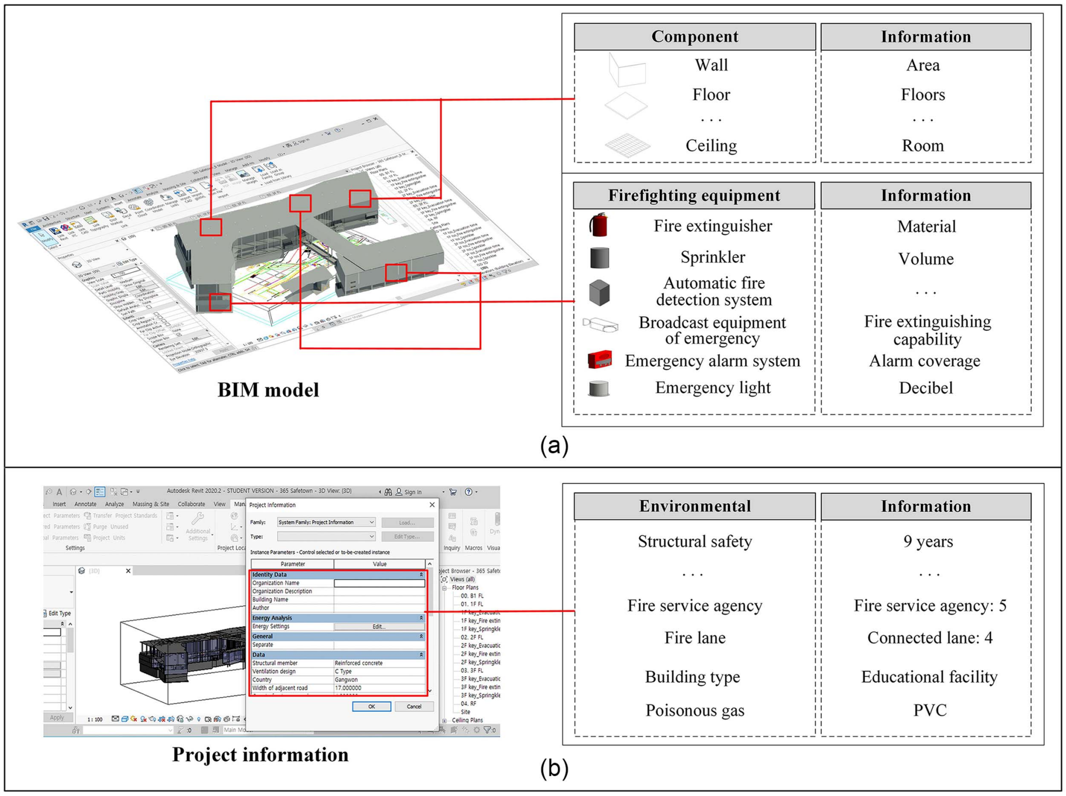


Fig. 2. Evaluation algorithm for "S" cultural and assembly facility.

criteria (fire resistance, fire extinguishing, etc.) were established based on building fire safety standards in South Korea. The BIM model was generated with physical and environmental data using Revit software. The dynamo-based evaluation algorithm, containing evaluation criteria, automatically evaluated performance taking into account the physical and environmental characteristics of the building. The results showed that Scenario 1 had 30.9 points and Scenario 2 had 38.2 points. The best performer, Scenario 3, had 60.3 points, reflecting the building component, firefighting equipment, and environmental elements that prevent and respond to building fires. While this study selected evaluation elements by identifying the causes of major fire incidents in South Korea, there were only five case studies. Furthermore, to implement the BIM-based evaluation method for existing buildings, there is a need for standardized solutions, such as systematic definitions of evaluation elements and assessment methods.

The proposed BIM-based framework automatically evaluates building fire safety performance, making it usable by both experts and nonexperts. This framework helps building owners and managers enhance fire safety performance by identifying areas for improvement. The framework significantly contributes to the automated evaluation of fire safety performance of buildings based on BIM, providing a platform for future research to further emphasize and explore environmental improvements. Also, it offers an integrated approach to building fire safety management, contributing to better strategies for fire prevention and response.



Component	Information
Wall	Area
Floor	Floors
. . .	. . .
Ceiling	Room

Firefighting equipment	Information
Fire extinguisher	Material
Sprinkler	Volume
Automatic fire detection system	. . .
Broadcast equipment of emergency	Fire extinguishing capability
Emergency alarm system	Alarm coverage
Emergency light	Decibel

Environmental	Information
Structural safety	9 years
. . .	. . .
Fire service agency	Fire service agency: 5
Fire lane	Connected lane: 4
Building type	Educational facility
Poisonous gas	PVC

Fig. 3. Configuration of evaluation elements in BIM model: (a) physical data; and (b) environmental data.

Table 4. Results for “S” cultural and assembly facility

Field	Element	Scenario 1	Scenario 2	Scenario 3
Building component elements	Structural member	2	2	4
	Window	0	0	0
	Door	1	1	3
	Stair	1	1	3
	Subtotal (16 points)	4	4	10
Firefighting equipment elements	Fire extinguisher	1	1	3
	Sprinkler	1	1	2
	Automatic fire detection system	1	1	2
	Emergency broadcast equipment	1	1	3
	Emergency alarm system	1	1	3
	Emergency light	1	1	3
	Smoke exhaustion equipment	1	1	1
	Subtotal (28 points)	7	7	16
Environmental elements	Fire service agency	1	3	3
	Fire lane	2	4	4
	Structural safety	1	2	2
	Building type	1	1	1
	Evacuation time	3	3	3
	Poisonous gas	2	2	2
	Subtotal (24 points)	10	15	15
Total (68 points)		21	26	41
Final score (out of 100 points)		30.9	38.2	60.3

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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