RESEARCH ARTICLE

Design and Implementation of a Fire Fighting System for a High-Rise Residential Building: A Case Study of SAMA Tower in Palestine

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Abstract

This paper describes the design and installation of a fire-fighting system in a high-rise building, the SAMA Residential Tower in Palestine. A sprinkler system, a standpipe system, a fire hose cabinet, a landing valve, externally accessible fire hydrants, and a Siamese connection are all included in this system. Additionally, it complies with NFPA 13, 14, and 20 codes, as well as those of the Palestinian and Jordanian governments. Hydraulic calculations were performed manually and confirmed using Elite Fire Protection software. The layouts were developed using AutoCAD, and 3D modeling was created in Revit to optimize the placement of components. All zones of the building will be protected by this integrated approach, which ensures reliable flow, sufficient pressure, and code compliance. In the application of an integrated design workflow, the coordination between fire protection components was improved, design errors were reduced, and implementation accuracy was enhanced. As a result of systematic validation between manual hydraulic calculations and software outputs, pressure and flow assurance was also more reliable. As a result, there was a clear increase in efficiency and performance for high-rise firefighting systems.

Keywords: fire-fighting system, high-rise residential building, NFPA standards, fire protection design.

1 Introduction

High-rise residential buildings pose unique challenges in ensuring occupant safety and minimizing property damage during fire incidents [1]. These challenges necessitate specialized design approaches that prioritize safety and efficiency. Among the most critical elements in such designs are fixed fire protection systems [2], which must be meticulously engineered to meet specific pressure, flow, and accessibility requirements.

Among the technological advances highlighted by Song et al. [3] are developments in material design,

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structural planning, and drones, robots, and the Internet of Things (IoT). As a result of these advancements, high-rise buildings can be made safer and fire prevention can be improved.

In Nairobi's CBD, Kironji [4] conducted a study that found significant deficiencies in fire safety, with sprinkler systems of 0% and disabled facilities lacking the most. There were notable shortcomings in fire detection and alarm systems of 14.29% and escape routes of 50% while portable fire extinguishers of 78.57% were among the better-performing systems. Improvements in inspection, maintenance, and design are recommended in the study.

An IoT-based fire safety monitoring and early warning system for high-rise buildings was proposed by Zhang [5]. The system combines hardware, including DS18b20 temperature sensors and relay control modules, with software, which contains fire warning instructions stored in a monitoring database. As a result of testing, monitoring recognition rates averaged 83.82% and 85.93%, reverse recognition errors averaged 0.0551 and 0.0371, and early warning response times averaged 4.81 s and 1.81 s, surpassing standard benchmarks. Despite high-rise building complexity, the system demonstrated high accuracy, minimal error, and fast response times.

According to Oaikhena et al. [6], Nigeria's population and land scarcity are driving high-rise residential buildings, which requires effective fire safety measures. A study conducted in Abuja emphasizes the importance of passive fire protection. A balanced approach to ensuring safer urban living environments is advocated, including tailored guidelines, stakeholder education, and stakeholder engagement.

According to Omar et al. [7], fire index systems are necessary to measure compliance with fire requirements and response efficiency in high-rise residential buildings in Sharjah. Compliance with fire requirements is correlated with successful emergency response. Based on automation and expert consultation, the systems evaluate fire risk, suppression systems, and evacuation facilities, enhancing emergency preparedness and measuring compliance with UAE fire legislation.

High-rise buildings in China have a significant impact on the use of urban land and the reputation of cities, but they present significant fire safety challenges, including evacuation challenges and increased fire risks at the top of commercial buildings. Gorbett et al. [8] present a case study of a nearly 500-meter-tall building that uses a life safety analysis and a fire simulation methodology, aligned with China's fire codes.

In addition to the aforementioned studies, there are numerous studies in the field showing the importance of safety in high-rise buildings. This study offers an in-depth exploration of a comprehensive fire-fighting system design for the SAMA Tower in Palestine, adhering to both international and local standards. The design process encompasses detailed fire risk analysis, precise hydraulic calculations, careful selection of components, and advanced layout simulations, providing a robust framework for fire safety in high-rise structures. This integrated methodology goes beyond mere verification, providing a systematic workflow that enhances coordination, validation, and design efficiency compared to traditional 2D design approaches.

1.1 Research Contribution and Novelty

Although fire-fighting system design is governed by well-established NFPA standards, this study contributes by presenting an integrated and validated engineering workflow that combines manual hydraulic calculations, software-based simulation, and BIM-based modeling within a single high-rise case study.

The novelty of this work does not lie in redefining fire protection principles, but in demonstrating how the integration of traditional NFPA-based calculations with Elite Fire software and Revit BIM modeling enhances design reliability, coordination efficiency, and implementation accuracy.

Through this integrated approach, the study highlights measurable improvements in design time reduction, error minimization, and system coordination compared to conventional 2D-based design processes. Additionally, the research provides a structured comparison between manual hydraulic calculations and software outputs, offering practical insights into discrepancies, safety margins, and validation limits. This contribution is particularly relevant for high-rise residential buildings, where system complexity, elevation effects, and multidisciplinary coordination significantly impact fire protection performance.

2 Background and Fundamentals of Fire Protection Systems

2.1 Fire Safety Principles

To effectively combat fire, it is essential to understand the fundamental principles of how fire ignites and sustains itself. Fire requires three critical components to start and burn: heat, fuel, and oxygen [9]. This combination is commonly called the fire triangle. Removing any one of these elements whether by cooling the heat source, eliminating the fuel, or cutting off the oxygen supply will extinguish the fire [10].

In addition to the fire triangle, a fourth element, the chemical chain reaction, plays a crucial role in sustaining a fire. This reaction perpetuates the combustion process, transforming the fire triangle into a fire tetrahedron [11]. The inclusion of this chemical chain reaction highlights the dynamic and self-sustaining nature of fire.

Effective fire protection systems are designed to address and control these elements. By targeting heat reduction, fuel removal, oxygen deprivation, or disruption of the chemical chain reaction, such systems prevent fires from starting or spreading, ensuring safety and minimizing damage.

2.2 Types of Fire Protection

Fire protection is categorized into two types [12]: passive fire protection, which includes fire-resistant walls, doors, and barriers to prevent fire spread, and active fire protection, which involves systems like sprinklers, fire cabinets, hydrants, and pumps to directly combat fires.

2.3 Fire Suppression Methods

The most common method of extinguishing fires is with water. Sprinklers are widely used due to their speed and reliability. Additional methods include water mist (fine droplets), foam (for fuel-based fires), and gas systems (ideal for sensitive environments like server rooms). In this study, we focused on a water-based sprinkler system because it is simple, cost-effective, and compliant with local regulations.

3 Building Analysis and Fire Risk Assessment

3.1 Building Type

The SAMA Tower is a high-rise residential building featuring multiple floors of apartments, corridors, garages, and technical rooms as illustrated in Figure 1. It is classified as a residential occupancy according to building codes.

Figure 1. SAMA Tower residential building.

3.2 Fire Hazard Class

The fire load indicates the quantity of combustible material present within a building. It is calculated using equation (1):

$$\text{Fire Load}\left(\frac{\text{MJ}}{\text{m}^2}\right) = \frac{\text{Mass} \times \text{Calorific value}}{\text{Area}} \tag{1}$$

The estimated materials include 500 kg of wood, 200 kg of plastic, 100 kg of paper/textiles, within a floor area of $1{,}250\,\text{m}^2$, resulting in a fire load of approximately $13.2\,\text{MJ/m}^2$, which falls within the range for Ordinary Hazard Group 1 $(10 - 20\,\text{MJ/m}^2)$ [13, 14].

4 Fire System Design and Components

4.1 Sprinkler System

A wet-pipe sprinkler system was selected instead of a dry system because it keeps the pipes constantly filled with water, making it the most common and straightforward system to install. Sprinklers are heat-activated; when the glass bulb breaks (typically at 68°C), water flows immediately. The sprinkler type used is standard spray, pendent type, with a K-factor of 5.6. Each sprinkler covers an area of 12 m^2, and the layout follows a tree distribution with simple, direct branches.

Adherence to NFPA 13 spacing requirements, as shown in Table 1, was maintained. The sprinkler spacing was set at 3 m by 4 m, with a maximum of 8 sprinklers per branch. According to the code, sprinklers must be at least 1.8 m apart, and the distance between each sprinkler and walls or obstacles should not exceed half the spacing between sprinklers or be less than 10 cm [15].

Table 1. Protection area and spacing [10].

Construction	System	Protection Area		Spacing (maximum)	
Type	Type	ft^2	m^2	ft	m
All	All	130	12,1	15	4.6

4.2 Fire Hose Cabinets (FHC)

Fire hose cabinets (FHCs) enable untrained individuals to combat fires before firefighters arrive, equipped with a hose, nozzle, and valve. In the used design [16], FHCs are strategically placed near exits, stairs, and garages, ensuring coverage of 25 m in all directions. The cabinets are semi-recessed (partially in the wall), provide a flow rate of 125 GPM, and require a pressure of 65 psi.

4.3 Landing Valves

Landing valves supply water to firefighter teams, strategically placed at stairwells for use by trained personnel only, as their high-pressure outlets are unsafe for public use. In the current design, one landing valve is installed on each floor.

4.4 Hydrants and Siamese Connections

Hydrants are positioned outside the building, spaced less than 30 m apart, to facilitate firefighting from fire trucks. A Siamese connection, featuring at least two 2.5" ports with a flow capacity of 250 GPM each, enables fire trucks to pump water into the building when necessary [15]. The hydrant flow rate aligns with the overall system flow, and the Siamese connection is located near the main entrance and hydrants.

4.5 Pumps and Piping

Three pumps were selected for the system [17]: the main pump, an electric pump that handles normal operation and supplies total system demand; the jockey pump, a small pump that maintains system pressure to prevent frequent activation of the main pump; and the diesel pump, a backup pump that matches the main pump's flow and pressure in case of power failure. Pipes are made of Schedule 40 carbon steel, with diameters chosen to maintain velocities of 6–8 ft/s for sprinklers and fire hose cabinets (FHCs) and 10–15 ft/s for hydrants and Siamese connections. Sprinkler mains are 6 inches, FHC pipes are 4 inches, and Siamese/hydrant lines are 6 inches [15, 18].

4.6 Valves

The fire-fighting system employs various valves to control water flow and facilitate maintenance. Gate valves isolate sections of the system, while check valves prevent backflow. Alarm check valves activate alarms when sprinklers are triggered, and test and drain valves enable system testing and water removal [17]. Pressure gauges monitor water pressure at critical points, and butterfly valves are used in confined spaces. Zone control valves divide the building into zones and signal alarms. Flexible connections between pumps and pipes minimize stress and vibration. Ball check valves provide backflow prevention with minimal pressure loss, and anti-vortex plates at pump inlets prevent air entry, ensuring smooth water flow [17].

5 Hydraulic Calculations

5.1 Sprinkler Flow

NFPA 13 was used to determine the design area and required density for ordinary hazard, as shown in Figure 2.

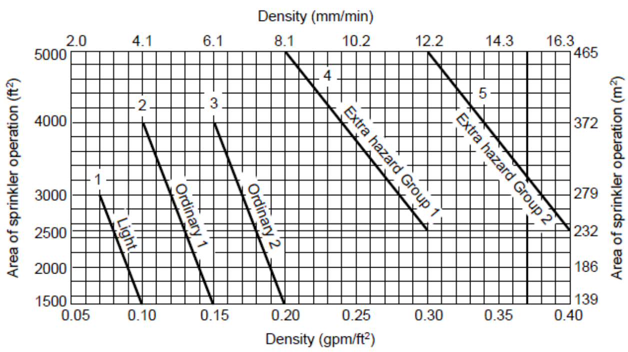


Figure 2. Area of sprinkler-design density [16].

The flow is calculated using Equation (2):

$$Q = \text{Density } (D) \times \text{Design Area } (A) \qquad (2)$$

where $D = 0.15\,\text{gpm/ft}^2$ (for Ordinary Hazard Group 1) and $A = 1500\,\text{ft}^2$ (remote area per NFPA 13). Thus:

$$Q = 0.15 \times 1500 = 225\,\text{GPM}$$

(total design flow for the sprinkler remote area).

Each sprinkler has a minimum flow of approximately 19.5 GPM (based on $0.15 \times 130\,\text{ft}^2$), but the total system demand is governed by the density over the full design area, not by multiplying per-sprinkler flow by the number of operating sprinklers. The number of most remote sprinklers in the design area is approximately $1500/130 \approx 11.5$, rounded up to 12 for conservative estimation in some methods, but the correct total sprinkler flow is density $\times$ area = 225 GPM (excluding hose demand).

5.2 Fire Hose Cabinets (FHC) Flow

Each fire hose cabinet (FHC) requires 125 GPM, and the design must account for two cabinets at the farthest point, resulting in a total FHC flow of 2 × 125 = 250 GPM. The required pressure is 65 psi at the outlet.

5.3 Total Flow and Pressure

5.3.1 Total Flow (GPM)

The total designed flow combines the sprinkler and FHC flows as shown in equation (4).

$$\text{Total Flow} = \text{Sprinkler Flow} + \text{FHC Flow} \tag{3}$$

The manual calculation yields a combined sprinkler + FHC flow of approximately $225 + 250 = 475\,\text{GPM}$ (excluding additional standpipe or landing valve demands in worst-case scenarios).

This calculation assumes an ideal flow pattern without considering the pressure losses that affect the flow. The flow is modeled using Equation (5):

$$Q = \frac{K}{\sqrt{P}} \tag{4}$$

where Q is the flow (GPM), K is the water flow coefficient (GPM psi$^{0.5}$), and P is the pressure at the sprinkler (psi).

5.3.2 Total Pressure (psi)

The total pressure (psi) can be expressed using Equation (6):

$$P_{\text{Total}} = P_{\text{FHC}} + P_{\text{Elevation}} + P_{(\text{Friction + Fittings})} \tag{5}$$

where $P_{\text{FHC}} = 65\,\text{psi}$ is the pressure at the cabinet outlet, $P_{(\text{Friction})}$ represents the frictional pressure loss due to flow through pipes, $P_{\text{Elevation}}$ accounts for pressure loss due to elevation differences, and $P_{(\text{Fittings})}$ includes additional losses from valves, elbows, tees, etc.

The Hazen-Williams equation, shown in Equation (7), is used to calculate frictional pressure losses due to pipe length and fittings:

$$h_f = 4.52 \cdot \frac{Q^{1.85} L}{C^{1.85} D^{4.87}} \tag{6}$$

where h_f is the frictional pressure loss (psi), Q is the total flow rate in the pipe (GPM), L is the pipe length (ft), C is the roughness coefficient (unitless, typically 120 for steel), and D is the pipe diameter (inches).

The equivalent length method is used to account for pressure losses from elbows, tees, and valves by representing the length of straight pipe that would cause the same pressure drop. Therefore:

$$L_{\text{Total}} = L_{\text{Pipe}} + L_{(\text{Fittings})} \tag{7}$$

where L_{Total} is the total length that is calculated as the sum of the longest pipe length L_{Pipe} and the equivalent length of the fittings $L_{(\text{Fittings})}$.

By applying these equations, the total pressure for the system can be determined, which affects the total flow. The flow is expected to exceed 500 GPM, as demonstrated in Elite software.

6 Software Simulation with Elite Fire

Elite Fire Protection Software was used to simulate the hydraulic performance of the system, calculating the pressure and flow alongside the effects of losses on them.

6.1 Input Data

In the software, the following inputs were entered:

1. Building height and floor levels.
2. Hazard classification (Ordinary Hazard Group 1).
3. Type of system: Sprinkler and Standpipe.
4. Pipe materials and diameters.
5. Elevation of each node (floor or component).
6. Fittings, lengths, and K-factors.

6.2 Simulation

Two simulations were run in the software:

1. Sprinkler system simulation.
2. Fire hose cabinet system simulation.

6.3 Results Summery

To validate the hydraulic performance of the designed fire-fighting system, manual calculations based on NFPA guidelines were compared with Elite Fire software simulation results, as detailed in Table 2. Key parameters including flow rate, pressure at remote points, and total head loss were evaluated at critical demand locations within the system.

Manual calculations estimate a base demand of around 475–500 GPM, while Elite Fire software

Table 2. Fire component characteristics.

Component	Hydraulic Calculations		
	Flowrate (GPM)	Pressure (psi)	Pipe Diameter (inch)
Sprinklers	314.85	75	6
Fire Hose Cabinets	284.81	127.3	4
Landing Valves	250	65	6
Hydrants	600	127.3	6
Siamese	500 – 600	12 bar (from truck)	6

simulation, incorporating real-world losses and concurrent demands from sprinklers, FHCs, and standpipes, determines the total system flow to be approximately 600 GPM under the most demanding conditions. Results showed close agreement between manual calculations and software outputs, with minor differences observed in pressure losses and node pressures. The variations are primarily attributed to differences in modeling assumptions, including equivalent pipe lengths, minor loss coefficients, and iterative balancing software algorithms.

It is important to note that manual calculations make use of conservative assumptions, whereas software provides a more detailed representation of fittings and elevation effects. The result is slight deviations within acceptable engineering tolerances.

6.4 Fire Water Capacity

The amount of water required for Ordinary Hazard Group 1 for 60 minutes can be calculated using Equation (9):

$$C = \frac{Q_T \times 3.78 \times \text{Time}}{1000} \tag{8}$$

where Q_T is the total flow rate and Time is the duration for extinguishing the fire. Substituting the values, the calculation is:

$$C = \frac{600 \times 3.78 \times 60}{1000} = 136.08\,\text{m}^3 \tag{9}$$

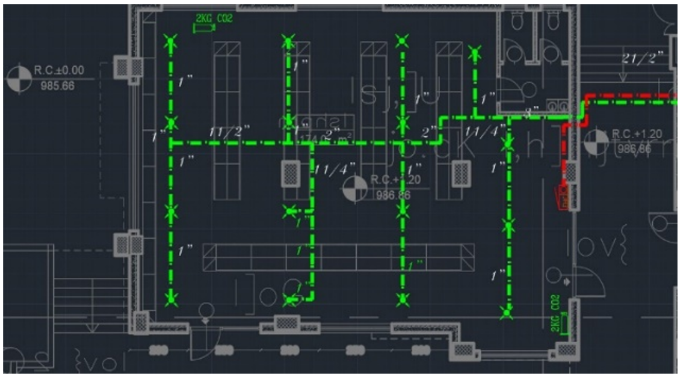
Therefore, the required water volume is 136.08 cubic meters.

7 CAD and Revit Modeling

AutoCAD was used for creating 2D plans, while Revit was used for developing 3D models to prepare the system for real construction.

7.1 AutoCAD Layouts

AutoCAD was used to draw pipe paths, connections, and risers, show the positions of pumps, cabinets, and sprinklers, and measure pipe lengths needed for hydraulic calculations, as illustrated in Figure 3. Figure 3(a) shows the sprinkler distribution over the mezzanine, while Figure 3(b) illustrates the riser connection with pumps.



(a) Sprinkler distribution over the mezzanine.

(b) Raiser connection with pumps

Figure 3. AutoCAD 2D modeling.

7.2 Revit 3D Models

Revit allowed the creation of realistic 3D views of the system, helping to avoid conflicts with structural or architectural elements, show riser connections and vertical pipes between floors, and present the system visually to others, as illustrated in Figure 4. The figure includes 3D representations of sprinklers, risers, pumps, valves, and pipe networks in garages and apartment floors, where Figure 4(a) shows the Fire Hose Cabinet (FHC) in the garage, Figure 4(b) illustrates the pipe distribution over the garage, Figure 4(c) shows riser distribution, Figure 4(d) presents a sprinkler head at the mezzanine, Figure 4(e) a sprinkler head along the line, Figure 4(f) a landing valve, Figure 4(g) a hydrant and Siamese connection, and Figure 4(h) the pump rooms.

8 Results and Discussion

8.1 System Performance

The system meets all fire protection goals. Water reaches all zones at the appropriate pressure, thus ensuring adequate coverage. The sprinkler system and fire cabinet meet code demands, while pipe diameters maintain recommended velocities (6–15 ft/s). Additionally, pressure losses due to elevation and fittings are effectively managed, ensuring optimal system functionality.

Aside from hydraulic validation, BIM-based modeling using Revit facilitated effective coordination among mechanical, electrical, architectural, and structural systems. The integration of these disciplines substantially reduced clashes, rework, and coordination errors, leading to notable savings in both design time and implementation effort. This improvement is illustrated in Figures 5 and 6. Specifically, Figure 5 demonstrates project delivery performance with BIM/Elite integration, showing a 60% reduction in design time, a 75% decrease in coordination effort, and an 80% reduction in revision cycles compared to traditional 2D/manual approaches.

Figure 6 illustrates the project delivery costs associated with BIM/Elite integration. When compared to a traditional 2D/manual system, the use of BIM/Elite results in 15-30% cost savings, 50% less material waste, and 60% fewer rework/change orders.

8.2 Code Compliance

The system adheres to multiple standards, ensuring safety and reliability. It complies with NFPA 13 for sprinkler layout, density, and K-factor requirements. NFPA 14 standards for standpipe and fire hose cabinet pressure and flow are met, as are NFPA 20 requirements for pump types, valves, and backup systems. The system is also aligned with Palestinian and Jordanian codes, which specify component locations, spacing, and system zoning.

9 Challenges and Future Improvements

9.1 Challenges

In this study, several challenges were encountered as follows:

1. Pressure at Top Floors: Achieving adequate pressure at the highest levels required careful pump selection and accurate pipe sizing.
2. Fitting Losses: Elbows, tees, and valves introduced pressure losses, which were addressed by including equivalent pipe lengths in the calculations.
3. Complex Inputs for Elite: Detailed data entry for each pipe section, node, and fitting was necessary, as even minor errors could significantly impact results.
4. Local Code Integration: Balancing NFPA standards with local Palestinian and Jordanian codes required additional checks and adjustments to ensure compliance.

9.2 Future Improvements

Several recommendations for future improvements are as follows:

1. Smart Monitoring: Install sensors to monitor water flow, pump status, and pipe pressure in real-time during a fire.
2. Scheduled Maintenance: Conduct regular tests and inspections to ensure the system remains operational and ready for emergencies.
3. CPVC Pipes: Utilize lightweight CPVC pipes in concealed areas to reduce costs and overall weight.
4. Pressure-Reducing Valves: Install PRVs on lower floors to protect Fire Hose Cabinets (FHCs) from excessive pressure.

10 Conclusions and Future Works

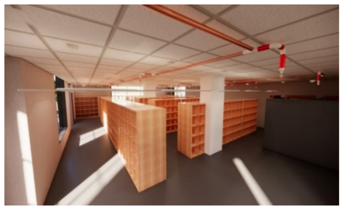
This work successfully designed and validated a comprehensive fire-fighting system for the SAMA Residential Tower, a high-rise building in Palestine. The system incorporates wet-pipe sprinklers, fire hose cabinets, landing valves, external hydrants, and a Siamese connection, complying with NFPA 13, 14, 20, and relevant local codes.

Through meticulous hydraulic calculations (manual and Elite Fire software validated), component selection, and integrated AutoCAD/Revit modeling,

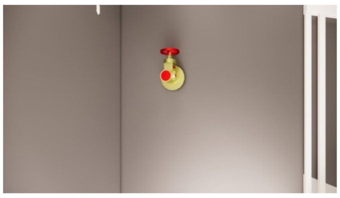

(a) FHC at garage.


(b) Pipe distributions over the garage.


(c) Raiser distributions.


(d) Sprinkler head at mezzanine.


(e) Sprinkler head on the line.


(f) Landing valve.


(g) Hydrant and Siamese.


(h) Pumps Rooms.

Figure 4. Revit 3D modeling.

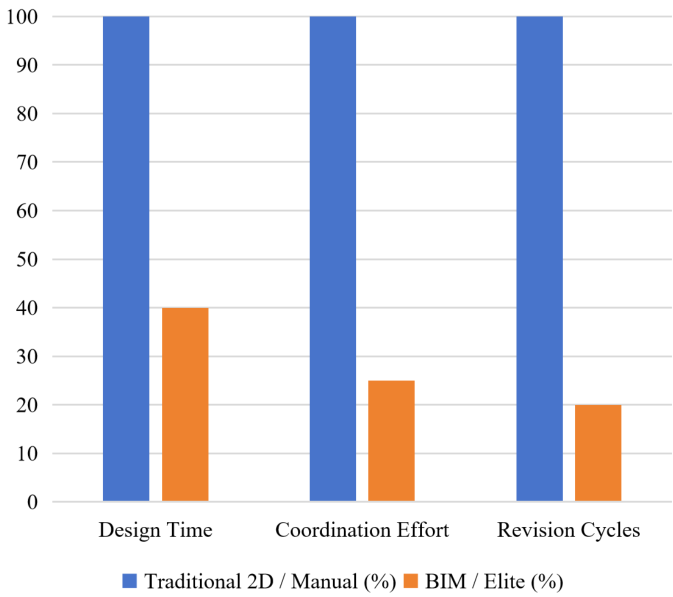


Figure 5. Traditional vs. BIM/Elite software integration comparison in terms of time and effort.

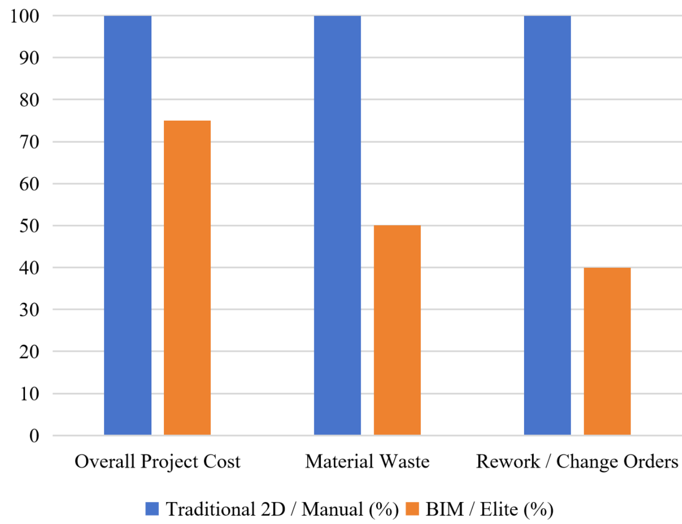


Figure 6. Traditional vs. BIM/Elite software integration comparison in terms of cost.

the design achieves adequate flow and pressure across all zones, reliable performance in worst-case scenarios (approximately 600 GPM total demand), and superior coordination with reduced errors compared to traditional 2D methods.

The approach ensures robust, code-compliant protection, markedly improving occupant safety and property preservation in high-rise residential settings.

10.1 Conclusions

This work successfully designed a comprehensive fire-fighting system for the SAMA Residential Tower, adhering to NFPA 13, 14, 20, and local fire codes, incorporating essential components such as sprinklers, fire cabinets, landing valves, hydrants, and Siamese connections, and ensuring comprehensive coverage of all areas inside and around the building, adequate water flow and pressure to all fire-fighting components, efficient system distribution without overdesign, and enhanced reliability supported by a backup diesel pump and Siamese connections, achieved through meticulous planning, detailed analysis of the building's requirements, hydraulic calculations validated by Elite software, and precise CAD/Revit modeling, resulting in a well-designed system that not only meets regulatory standards but also provides robust protection, ensuring the safety of the building and its occupants.

10.2 Recommendations

According to the experiences learned from this work, the following recommendations are made:

1. The future design of the building should include a smart monitoring system using sensors to detect and monitor pressure and flow levels inside the pipes, pumps, and along the valves.
2. Scheduled maintenance is essential to prolong the system's life by regularly checking components, testing pressure throughout the system, and ensuring pump operation to guarantee readiness.
3. Providing training for occupants, including fire drills and evacuation exercises, will improve evacuation times and enhance safety during emergency situations.

10.3 Future Works

Key areas for future research include:

1. Comparing the performance of wet-pipe and dry-pipe systems in buildings located in mixed climates with both hot and cold weather conditions.
2. Developing pipe materials to enhance their strength and resistance to mechanical corrosion and damage.
3. Improving water storage and recovery cycle systems to increase the efficiency of fire protection systems in dry and remote areas.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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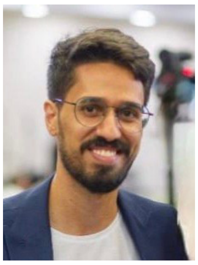

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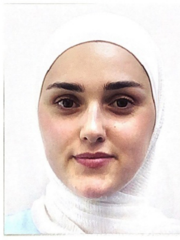

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