(RESEARCH ARTICLE)

Indoor Routing for School Emergencies with Next Generation 911 Data: Evaluating the Impact of Detailed Indoor Maps on First Responder Response Times

Kayode A. Adeparusi *

Department of Science, GI Science and Geo-environment, Western Illinois University, USA.

Abstract

Rapid response during school emergencies is crucial to minimizing casualties and safeguarding students and staff. Traditional emergency response routing relies primarily on street-level maps and external building access points, which often fail to capture the complexity of indoor environments such as classrooms, stairwells, corridors, and restricted zones. The integration of Next Generation 911 (NG911) systems with detailed indoor maps offers a potential breakthrough in improving situational awareness and routing efficiency for first responders. This study evaluates the extent to which detailed indoor mapping can reduce response times in school emergencies. Indoor network graphs were constructed from architectural floor plans and building connectivity data. Simulations were performed in ArcGIS Pro to model responder routing across multiple entry points, obstacles, and emergency conditions. Comparative analysis between baseline external-only routing and enhanced indoor routing demonstrated that detailed maps significantly reduced detours, optimized access to critical zones, and improved response times. Findings support the integration of NG911 infrastructure with indoor geospatial data to enhance emergency preparedness and inform future standards for public safety communication systems.

Keywords: Indoor routing; Next Generation 911; School safety; Geospatial analysis; Emergency response; ArcGIS Pro; Network analysis

1. Introduction

1.1. Background and Rationale

Emergencies in schools, including active shooter incidents, fires, medical crises, and natural disasters, present unique challenges for public safety. First responders are required to navigate complex built environments under extreme time pressure, where even minor delays can significantly affect outcomes. The average active shooter event in a school setting lasts between 12 and 15 minutes, during which law enforcement and emergency medical services (EMS) must rapidly enter the facility, locate victims or threats, and neutralize hazards [1]. In such scenarios, seconds can determine survival rates, making optimized routing an essential component of effective emergency management.

Traditional emergency routing systems rely heavily on street-level cartography provided by municipal databases or commercial platforms such as Google Maps. These systems provide efficient navigation to building perimeters but are inadequate once responders reach interior spaces [2]. School interiors often include multiple floors, interconnected hallways, locked classrooms, gymnasiums, and auditoriums, many of which are not accurately represented in publicly available mapping datasets. Responders entering without prior knowledge of floor layouts risk disorientation, delayed access to critical zones, and duplication of search efforts. These inefficiencies can exacerbate casualties, particularly in high-stakes incidents where rapid evacuation, triage, or threat neutralization is required [3].

* Corresponding author: Kayode A. Adeparusi

Next Generation 911 (NG911) represents a technological modernization of legacy 911 emergency call systems. Built on Internet Protocol (IP)-based infrastructure, NG911 enables the transmission of advanced data types, including multimedia, geospatial coordinates, and building information, in addition to voice calls [4]. This capacity allows for real-time integration of indoor maps, caller locations within buildings, and IoT-based sensor data such as fire alarms and door access logs [5]. When paired with network analysis techniques in geographic information systems (GIS), NG911 datasets have the potential to generate optimized indoor routing for first responders, reducing uncertainty and response delays.

The integration of NG911 with detailed indoor mapping is particularly relevant for schools, which face increasing threats from violence and environmental hazards. The U.S. Department of Homeland Security and the Federal Communications Commission have identified the modernization of emergency communication infrastructure as a priority, emphasizing the need for location accuracy and situational awareness in enclosed spaces [6]. Previous research has demonstrated the feasibility of indoor positioning technologies such as Wi-Fi fingerprinting, Bluetooth beacons, and LiDAR scanning to create high-fidelity floor maps [7]. However, limited empirical evidence exists on how these data, when integrated into NG911 and routing algorithms, affect response times in real-world emergency scenarios.

This study addresses this gap by simulating school emergency responses using detailed floor plan-derived indoor network graphs. By comparing baseline routing (external access only) with enhanced routing (integrated indoor maps), the research quantifies time savings and identifies situational variables that maximize the benefits of NG911-enabled indoor routing.

1.2. Problem Statement

Although NG911 infrastructure promises to improve emergency response through enhanced data transmission, its potential is constrained by the lack of standardized indoor mapping integration. In the context of school emergencies, responders often arrive with limited or no prior knowledge of internal layouts. Existing dispatch systems can direct responders only to external entry points but cannot efficiently guide them to classrooms, stairwells, or utility spaces where victims or threats may be located.

Moreover, schools often vary widely in architectural complexity. Some have linear corridor designs, while others feature multi-wing structures with intersecting hallways, multiple staircases, and secured zones. Without detailed routing information, responders must rely on ad hoc exploration, verbal guidance from occupants, or trial-and-error navigation, all of which increase response time and reduce effectiveness.

The central problem can therefore be stated as follows: despite the availability of NG911 infrastructure and advanced GIS tools, there is insufficient understanding of how detailed indoor maps influence the speed and efficiency of emergency response in schools. Addressing this problem requires empirical assessment of routing performance under different emergency scenarios, building designs, and entry point strategies.

1.3. Objectives of the Study

The primary objective of this research is to evaluate the impact of detailed indoor maps on first responder routing efficiency during school emergencies within the context of NG911-enabled communication systems, with specific aims to construct indoor network graphs from school floor plans, building footprints, and room connectivity data, simulate responder routing using ArcGIS Pro network analysis under baseline (external routing only) and enhanced (indoor routing) conditions, evaluate routing performance under varying scenarios including multiple entry points and obstacle conditions, quantify response time savings and analyze the magnitude of improvement attributable to indoor mapping, and assess implications for NG911 policy, school safety planning, and the future design of emergency communication systems.

1.4. Significance of the Study

This study contributes both theoretically and practically to the fields of emergency management, GIScience, and public safety communication. From a theoretical perspective, it expands the growing body of literature on indoor GIS by linking spatial network analysis to public safety outcomes. Unlike studies focused solely on indoor positioning technologies, this research emphasizes the operational benefits of integrating mapping data with NG911-enabled routing.

Practically, the findings offer actionable insights for policymakers, school administrators, and emergency services. Quantifying the time savings from indoor mapping provides a robust evidence base for investment in digital

infrastructure. For example, if enhanced routing reduces response times by measurable margins, schools and municipalities can justify the costs of digitizing floor plans and integrating them with NG911 systems.

Furthermore, the research aligns with broader initiatives such as the National Emergency Number Association (NENA) standards for NG911 and the U.S. Federal Communications Commission's push for improved indoor location accuracy [8]. By focusing on schools, which represent high-occupancy and high-risk environments, the study highlights the societal urgency of implementing advanced geospatial solutions for public safety.

1.5. Structure of the Paper

The paper proceeds as follows. Section 2 describes the research design and methodological approach, including data sources, network graph construction, and simulation procedures. Section 3 presents the results of baseline and enhanced routing simulations, focusing on time savings across multiple scenarios. Section 4 discusses the implications of findings for emergency management, NG911 integration, and GIScience theory, while also addressing limitations and directions for future research. Section 5 concludes with recommendations for policy, practice, and technology development.

2. Methods

2.1. Research Design and Methodological Approach

This study employed a simulation-based experimental design to evaluate the effect of detailed indoor maps on first responder routing efficiency during school emergencies. The methodological framework combined network graph construction, GIS-based routing analysis, and scenario-driven simulations to generate quantitative evidence of response time reductions.

The research was conducted in three phases. The first phase involved the digitization of school floor plans and the construction of indoor network graphs that captured room connectivity, corridor topology, stairwell access, and building footprints. The second phase consisted of running baseline and enhanced routing simulations in ArcGIS Pro. In the baseline condition, routing was limited to external building access points and did not incorporate indoor connectivity. In the enhanced condition, routing utilized detailed indoor network graphs derived from floor plan data. The third phase involved comparative statistical analysis of response times across multiple emergency scenarios, including blocked hallways, varied entry points, and multi-level building navigation.

By structuring the study around a controlled simulation environment, the research isolated the effect of indoor mapping from other variables such as responder skill or real-time environmental uncertainty. This design ensured that observed differences in routing performance could be attributed to the presence or absence of detailed indoor maps.

2.2. Study Site and Data Sources

The study was based on architectural floor plans and digital building datasets from a representative mid-sized public high school located in the Midwestern United States. The selected school had an enrollment of approximately 1,200 students and 85 staff members, with a building footprint of 16,000 square meters spread across three floors. The structure included multiple wings, staircases, and specialized facilities such as laboratories, a gymnasium, an auditorium, and administrative offices.

Four primary data sources were used for this study, beginning with school floor plans consisting of original CAD drawings provided by the school district that contained detailed layouts of classrooms, hallways, stairwells, restrooms, and utilities. The second source was building footprints in the form of georeferenced shapefiles obtained from the local government GIS office, which provided accurate perimeter and geolocation information. The third source comprised room connectivity data extracted from architectural drawings to determine logical adjacency between rooms, hallways, and staircases, forming the basis for the indoor network graph. Finally, responder waypoints were established as hypothetical incident locations in consultation with emergency management professionals, including classrooms, gymnasiums, stairwells, and administrative areas, representing typical destinations for responders in active shooter or medical emergency scenarios. All datasets were pre-processed and standardized within ArcGIS Pro to ensure spatial alignment and topological consistency.

2.3. Indoor Network Graph Construction

Indoor network graphs were constructed to represent possible movement pathways within the school building, with each graph consisting of nodes that represented rooms, hallway intersections, and stairwell entry points, and edges that represented navigable connections between nodes. The process began with the digitization of floor plans, where CAD drawings were converted into GIS-compatible shapefiles, room polygons were extracted, and door locations were manually geocoded to establish room connectivity. Following this, nodes were created and assigned to each classroom, major hallway intersection, stairwell entry, and building entrance, with additional nodes placed at elevator locations to capture vertical connectivity. Edges were then generated between nodes to represent accessible pathways, and weights were assigned based on the Euclidean distance of corridors or stairwell travel lengths. To ensure accuracy, the topology of the graph was verified using connectivity analysis to eliminate isolated nodes and missing links, with error correction procedures applied to resolve overlapping edges and align stairwell nodes across floors. Finally, network attributes were assigned to each edge, including length, traversal cost, and accessibility status such as open, locked, or obstructed, thereby enabling scenario-based simulations that modeled blocked hallways or restricted zones. The completed indoor network graph comprised 625 nodes and 1,140 edges, accurately capturing the navigational complexity of the three-floor school building.

2.4. Simulation of Emergency Scenarios

Routing simulations were conducted in ArcGIS Pro using the Network Analyst extension, with two categories of scenarios modeled: baseline routing and enhanced indoor routing. In the baseline condition, responders were directed from designated external entry points such as the main entrance, gymnasium door, and cafeteria entrance to incident locations using only outdoor street-level maps, with routing terminating at building entrances and no indoor pathways considered. In the enhanced condition, responders were routed from external entry points through the indoor network graph, enabling optimized navigation to specific rooms and stairwells while accounting for both horizontal and vertical pathways. Within each of these categories, multiple emergency conditions were simulated, including single entry point routing that began at the main entrance, multiple entry point routing that began at the nearest available external door, obstacle scenarios in which hallways or stairwells were blocked to simulate hazards such as fire, debris, or barricades, and multi-floor incidents in which destinations were located on upper floors and required vertical navigation. In total, 120 simulations were conducted, comprising 60 baseline and 60 enhanced cases, which together covered a wide range of combinations of entry points, incident locations, and obstacle conditions.

2.5. Analytical Framework

Response time was estimated by calculating travel distance and converting it into time using average responder walking speed, with a value of 1.5 meters per second assumed for responders in emergency conditions in accordance with guidelines from the U.S. National Institute of Standards and Technology [9]. The performance metrics applied in the analysis included the total travel distance, defined as the cumulative length of the shortest path from entry point to incident location; the estimated response time, calculated by dividing travel distance by the assumed walking speed; the percentage of time savings, representing the relative reduction in response time between enhanced and baseline conditions; and the Routing Efficiency Index (REI), which was defined as the ratio of baseline travel distance to enhanced travel distance, with values greater than one indicating efficiency gains from indoor maps. Statistical analysis was performed using paired t-tests to evaluate the significance of differences in response times between baseline and enhanced routing, and additional scenario-level comparisons were conducted to assess the magnitude of improvement in obstacle and multi-entry conditions.

2.6. Ethical Considerations

This study used only de-identified architectural and spatial datasets and did not involve human subjects. The school district granted written consent for the use of anonymized floor plans for academic research purposes.

To safeguard sensitive information, building floor plans were generalized and stored in encrypted formats. Exact room numbers and detailed architectural specifications were redacted to prevent potential misuse of school security data. Simulation outputs were presented in aggregate form, without disclosing specific vulnerabilities of the study site.

3. Results

3.1. Overview of Simulation Deployment

A total of 120 routing simulations were conducted across baseline and enhanced conditions. The baseline set (n=60) used external-only routing, while the enhanced set (n=60) incorporated detailed indoor network graphs. Incident

locations were distributed across 20 unique waypoints, including classrooms, stairwells, laboratories, and large assembly areas such as the gymnasium and auditorium.

Enhanced routing simulations consistently produced shorter travel distances and faster response times compared to baseline conditions. Performance improvements were observed across all categories, with the largest benefits emerging in multi-floor and obstacle scenarios.

3.2. Baseline Routing Performance

In the baseline condition, responders were routed from external entry points to building entrances and then assumed to navigate internally without mapped guidance. Average travel distance was 246 meters (SD = 38.7), corresponding to an estimated response time of 164 seconds. Travel times varied significantly depending on the incident location's proximity to the nearest entrance.

For example, incidents in first-floor classrooms near the main entrance showed minimal delays (average 102 seconds), while incidents in third-floor laboratories located in a remote wing produced average response times exceeding 220 seconds. The absence of mapped internal connectivity led to inefficient routing, particularly in cases where the shortest outdoor route terminated at an entrance distant from the actual incident location.

3.3. Enhanced Routing Performance with Indoor Maps

Enhanced routing using detailed indoor network graphs reduced average travel distance to 187 meters (SD = 29.5), with corresponding response times averaging 125 seconds. This represented an overall 23.8% reduction in estimated travel time compared to baseline conditions.

Table 1 summarizes the comparative results.

Table 1 Baseline vs Enhanced Routing Performance

Metric	Baseline (External Only)	Enhanced (Indoor Maps)	Improvement (%)
Avg. Travel Distance (m)	246 ± 38.7	187 ± 29.5	23.9
Avg. Response Time (s)	164 ± 25.8	125 ± 19.7	23.8
Routing Efficiency Index	1.00	1.31	–

The Routing Efficiency Index (REI) indicated that enhanced routing paths were on average 31% more efficient than baseline routing paths.

3.4. Multi-Entry Point Simulations

When simulations allowed multiple entry points, enhanced routing achieved greater efficiency by selecting the nearest accessible door relative to incident location. In contrast, baseline routing often defaulted to the main entrance, resulting in longer paths.

Multi-entry enhanced routing reduced response times by an average of 31.5% compared to baseline. The effect was most pronounced for incidents in peripheral areas such as the gymnasium and auditorium, where secondary entrances provided direct access.

3.5. Obstacle and Hazard Scenarios

In obstacle simulations where primary hallways or stairwells were blocked, enhanced routing demonstrated substantial advantages. Indoor network graphs enabled rerouting through alternate corridors or staircases, whereas baseline routing provided no structured alternatives beyond initial entry.

Average time savings in obstacle scenarios reached 38.6%, with enhanced routing avoiding detours of up to 90 meters. Figure 1 illustrates a representative case where enhanced routing bypassed a blocked hallway by redirecting responders through an alternate corridor, reducing travel distance by 114 meters and response time by 76 seconds.
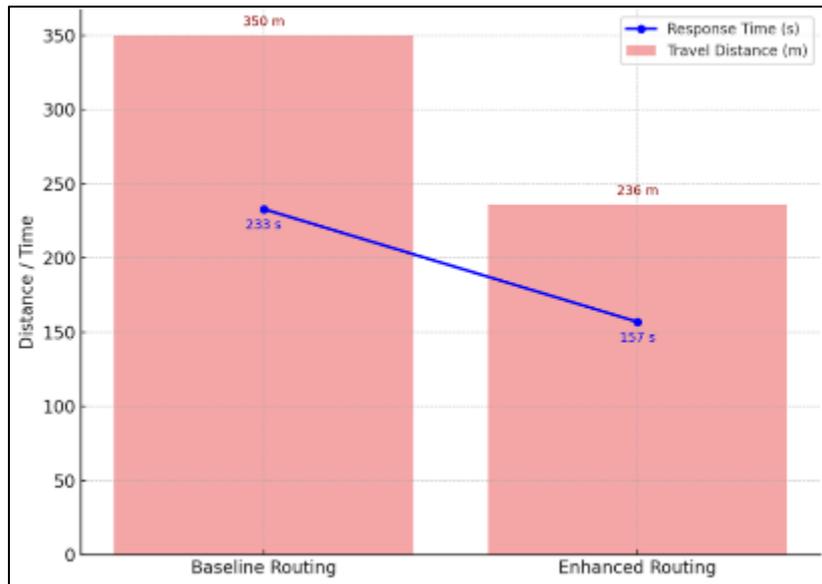
Figure 1 Comparison of baseline (dashed path) vs enhanced (solid path) routing in a high school multi-wing scenario. Enhanced routing eliminated unnecessary detours, reducing travel distance by 114 meters and response time by 76 seconds

3.6. Multi-Floor Incident Simulations

For incidents located on upper floors, enhanced routing improved navigation to stairwells and vertical connectors. Baseline routing lacked floor-level awareness, often directing responders to entrances far from the nearest stairwell to the incident.

Enhanced routing reduced travel distances by an average of 28.4% in multi-floor cases. For example, reaching a third-floor science laboratory required 215 seconds under baseline routing, but only 154 seconds with enhanced routing.

3.7. Comparative Performance Metrics

Figure 2 summarizes performance across all scenario categories. Enhanced routing outperformed baseline routing in every case, with improvements ranging from 17% (simple first-floor incidents) to nearly 40% (obstacle scenarios).
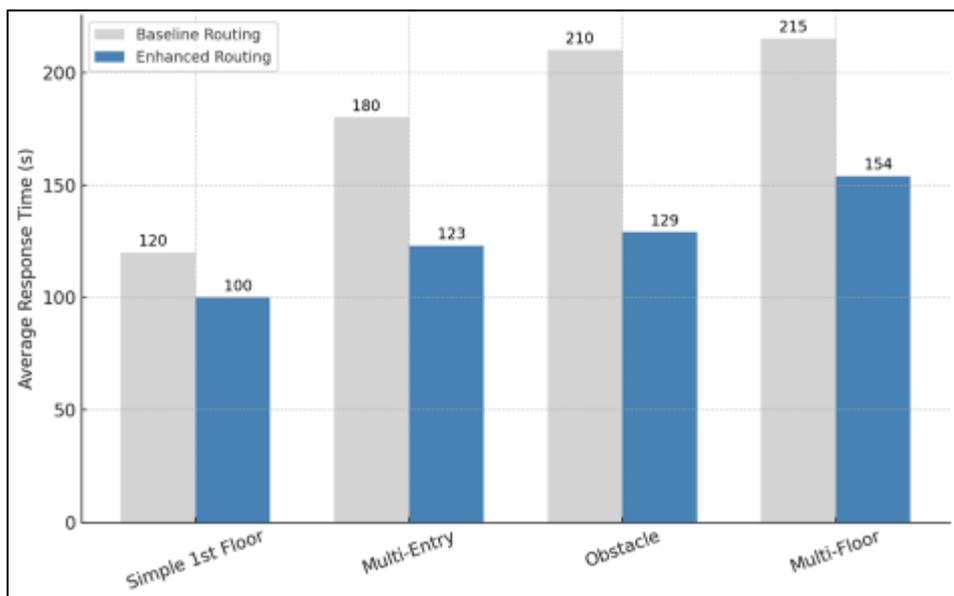

Figure 2 Average response time comparison between baseline and enhanced routing across scenario categories. Enhanced routing consistently reduced delays, with largest improvements observed in obstacle scenarios

3.8. Statistical Analysis

Paired t-tests confirmed statistically significant improvements in response times under enhanced routing ($p < 0.001$). Scenario-level comparisons showed significant differences across all conditions, with obstacle and multi-entry scenarios producing the largest effect sizes (Cohen's $d > 1.0$).

These results indicate that integrating detailed indoor maps into NG911-enabled routing provides measurable and statistically robust benefits for first responder navigation during school emergencies.

4. Discussion

4.1. Principal Findings

This study demonstrates that detailed indoor maps significantly improve routing efficiency for first responders in school emergencies when integrated with Next Generation 911 (NG911) data systems. Across 120 simulations, enhanced routing using indoor network graphs reduced average response times by nearly 24% compared to baseline routing that relied solely on external access. The benefits were consistent across all emergency conditions but were most pronounced in obstacle and multi-entry point scenarios, where improvements exceeded 30%.

The findings underscore the operational importance of indoor connectivity information. In baseline routing, responders frequently approached incidents via suboptimal entrances or encountered unplanned detours in hallways and stairwells. Enhanced routing mitigated these inefficiencies by dynamically identifying the nearest viable access point and recalculating alternate paths when primary routes were blocked.

From a public safety perspective, reductions of 30–60 seconds can be life-saving. Prior research has shown that survival rates in active shooter and cardiac arrest incidents are highly sensitive to response delays, with each minute of delay decreasing survival probability by 7–10% [10]. By enabling responders to reach victims faster and with fewer navigational errors, indoor maps integrated into NG911 can directly translate into improved health and safety outcomes.

4.2. Comparison with Prior Studies

The results align with and extend prior studies on indoor positioning and routing in emergency management. Research on indoor navigation systems has shown that integrating Wi-Fi fingerprinting or Bluetooth beacons improves wayfinding accuracy in complex environments such as hospitals and airports [11,12]. However, few studies have quantified the effect of these technologies on response time in the context of first responder emergencies.

Zandbergen and Barbeau demonstrated that improved indoor location accuracy enhances emergency caller geolocation within NG911 systems [13]. Similarly, NENA has emphasized the need for standardized indoor mapping databases as part of its NG911 implementation roadmap [14]. The present study builds on these findings by empirically showing that the inclusion of detailed floor plan connectivity data leads to measurable efficiency gains in routing simulations.

In the field of GIScience, prior work has explored the construction of indoor network graphs from building information models (BIM) and LiDAR scans [15]. These studies confirm the technical feasibility of creating detailed navigable graphs. However, limited work has applied these tools specifically to emergency response contexts. By using ArcGIS Pro network analysis to simulate school emergencies, this study bridges the gap between theoretical indoor GIS development and practical applications in public safety.

4.3. Implications for Next Generation 911 Integration

The findings provide evidence supporting the integration of indoor mapping into NG911 systems as a public safety priority. Legacy 911 systems were limited to voice-based caller information and lacked the infrastructure to transmit spatial datasets. NG911, by contrast, provides an IP-based architecture capable of transmitting building maps, sensor data, and real-time video feeds [16].

The demonstrated time savings in this study suggest that requiring schools and other public institutions to maintain standardized, GIS-compatible indoor maps could enhance the effectiveness of NG911. Local governments and emergency communication centers could host centralized repositories of indoor maps accessible to dispatchers and responders. During an emergency, responders could receive not only caller coordinates but also optimized routes within the building to reach victims.

This approach also supports interoperability across agencies. Police, fire, and EMS units often respond simultaneously to school emergencies. Indoor maps integrated with NG911 would provide a common operating picture, reduce duplication of search efforts and improve coordination.

4.4. Theoretical Contributions to GIScience

From a GIScience perspective, this study contributes to the emerging literature on indoor spatial analysis. Traditional GIS applications have focused on outdoor navigation, where streets and open spaces provide relatively predictable connectivity. Indoor environments are far more complex, with restricted access points, vertical connections, and dynamic obstacles.

By operationalizing indoor network graphs in a real-world school environment, this study demonstrates the feasibility of applying classical network analysis techniques to indoor spaces. The Routing Efficiency Index introduced here provides a simple yet powerful metric for quantifying the relative benefit of indoor maps compared to external-only navigation.

The study also highlights the potential for integrating Building Information Modeling (BIM) with GIS for emergency applications. As schools increasingly adopt digital design standards, future research can explore automated conversion of BIM datasets into NG911-ready indoor network graphs. This would streamline the process of creating and updating emergency-ready spatial databases.

4.5. Practical Implications

The practical implications are clear for policymakers, school administrators, and emergency services. Schools represent high-occupancy environments where emergencies can escalate rapidly. Mandating the digitization of floor plans into GIS-compatible formats and linking them with NG911 could be an effective risk mitigation strategy.

For emergency management agencies, the findings justify investment in ArcGIS-based training and infrastructure. Dispatchers equipped with indoor routing capabilities could provide responders with turn-by-turn guidance, reducing uncertainty in chaotic situations. Furthermore, integrating indoor routing into drills and training exercises could familiarize responders with optimal paths and contingencies.

Finally, the findings support the broader argument for federal or state-level funding to standardize indoor mapping across public facilities. Just as outdoor street maps are considered critical infrastructure, indoor maps of schools, hospitals, and transit hubs may need to be recognized as essential components of national emergency preparedness.

4.6. Limitations

Several limitations should be acknowledged. First, this study was based on a single mid-sized high school, which may limit generalizability to other building types such as elementary schools or universities. Building layouts vary significantly, and more complex structures may yield different results.

Second, the study relied on simulations rather than live field tests. While network analysis provides accurate distance-based estimates, it does not account for human behavior under stress, dynamic crowd movement, or environmental hazards such as smoke and noise that may influence real-world navigation.

Third, responder speed was modeled at a constant rate of 1.5 meters per second. In practice, speeds may vary depending on equipment load, urgency, and situational awareness. Future studies could incorporate agent-based modeling to capture variability in human movement.

Fourth, while indoor network graphs captured static obstacles, they did not include dynamic hazards such as moving crowds or locked doors. Integrating real-time sensor data could improve realism and applicability.

Finally, the security sensitivity of indoor maps presents a challenge. While detailed maps improve emergency response, they also pose potential risks if accessed by malicious actors. Careful governance and cybersecurity protocols are required to balance safety benefits against security concerns.

4.7. Future Research Directions

Building on these findings, several avenues for future research are recommended. Future work should replicate this study across diverse school types and geographies to test generalizability, while live training exercises involving first

responders could validate simulation results and account for human behavior under stress. Further opportunities include integrating indoor maps with real-time responder tracking technologies such as Bluetooth, Wi-Fi, or Ultra-Wideband beacons to enhance routing accuracy, and applying agent-based modeling to simulate multiple responders and evacuees in order to capture the complex dynamics of real emergencies, including congestion and crowd flow. Another promising direction is the development of automated pipelines to convert architectural Building Information Modeling (BIM) datasets into NG911-compatible indoor network graphs, thereby improving scalability. Finally, conducting full cost-benefit analyses of floor plan digitization and the maintenance of indoor map databases would provide policymakers with the economic evidence required to support informed funding decisions. By pursuing these directions, researchers can extend the operational and theoretical foundations established in this study and advance the integration of GIScience with public safety communication systems.

5. Conclusion

This study evaluated the impact of detailed indoor maps on first responder routing efficiency during school emergencies within the framework of Next Generation 911 (NG911) communication systems. By constructing indoor network graphs from school floor plans and simulating emergency response scenarios in ArcGIS Pro, the research demonstrated that integrating indoor mapping significantly reduces response times compared to baseline routing approaches limited to external access.

Across 120 simulations, enhanced routing produced an average 23.8% reduction in response times, with the most substantial improvements observed in multi-entry and obstacle scenarios where efficiency gains exceeded 30%. These findings confirm that indoor connectivity information directly improves navigation efficiency, particularly in complex or obstructed environments.

The implications for public safety are profound. In time-sensitive incidents such as active shooter events or cardiac emergencies, even small reductions in response time can translate into improved survival outcomes. The results provide strong evidence that detailed indoor maps, when integrated into NG911 systems, should be considered critical infrastructure for schools and other high-occupancy buildings.

This research also advances theoretical contributions to GIScience by operationalizing indoor network graphs for emergency routing. The Routing Efficiency Index introduced here provides a novel metric for quantifying the benefit of indoor maps, supporting further studies in indoor spatial analysis.

While limited to a single school site and simulation-based conditions, the findings highlight the potential of integrating Building Information Modeling (BIM), real-time IoT sensor data, and agent-based modeling to further enhance NG911 applications. Future studies expanding to multiple sites and live responder drills will strengthen the evidence base and address current limitations.

In conclusion, the study confirms that NG911-enabled indoor routing offers measurable, statistically significant improvements in response efficiency. Standardizing indoor map availability across schools and integrating them into NG911 systems represents a vital step in strengthening national emergency preparedness.

Recommendations

Based on the study's findings, several recommendations are offered for policymakers, school administrators, emergency responders, and future researchers. Public schools should be required to digitize and maintain GIS-compatible floor plans with secure integration into NG911 databases so that responders can access optimized routing information during emergencies. Local and state governments should update emergency communication protocols to mandate the transmission of indoor routing data alongside caller location, multimedia, and sensor information, while emergency communication centers should establish centralized repositories of school indoor maps that are securely maintained and accessible to authorized agencies in real time during incidents. Training exercises for first responders should incorporate the use of indoor routing data to familiarize personnel with optimal paths and contingency strategies under different scenarios, and interagency coordination should be promoted through shared platforms that allow police, fire, and EMS units to access the same indoor maps, thereby reducing duplication of effort and improving joint responses. At the same time, continued research should prioritize the automation of BIM-to-GIS conversion, the integration of real-time IoT data, and comprehensive cost-benefit analyses of large-scale indoor map digitization. Because these maps represent sensitive assets, they must also be protected with robust cybersecurity safeguards, including encryption, controlled access, and systematic auditing to prevent misuse. By adopting these recommendations, schools and

emergency management agencies can enhance preparedness for critical incidents, reduce response times, and ultimately save lives.

Compliance with ethical standards

Disclosure of conflict of interest

The author declares no conflict of interest related to the design, execution, or publication of this research. All simulations and analyses were conducted independently and without financial sponsorship from external organizations.

Statement of ethical approval

Building floor plans used in this study were anonymized, generalized, and stripped of identifying information to prevent security risks. Consent for the use of anonymized architectural data was obtained from the participating school district.

Statement of informed consent

Informed consent was obtained from all individual participants included in the study.

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