

AI-Assisted VR Simulation for Predicting and Minimizing Evacuation Congestion in School Shooting Emergencies

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ABSTRACT

School emergencies involving violent attacks often lead to unpredictable evacuation behavior. Panic, congestion, and avoidance of the threat can direct students away from the nearest exits and create dangerous bottlenecks. Existing evacuation systems and building designs are typically evaluated using static routing methods that do not adapt to real-time crowd conditions. This limits their ability to prevent or reduce congestion during an active emergency. The study proposes the development of an AI-assisted, Unity-based virtual reality (VR) evacuation simulator that models student evacuation behavior during a simulated school-shooting emergency at the Systems Plus College Foundation (SPCF) campus. The system integrates a Gated Recurrent Unit (GRU) neural network to predict congestion in critical corridors and exits. It also utilizes the D* Lite adaptive pathfinding algorithm that reroutes evacuees away from forecasted bottlenecks in real time. The proposed GRU–D* Lite approach will be benchmarked against conventional A* routing across four performance measures: evacuation time, congestion level, route utilization, and evacuation success rate. The study will also test alternative building configurations, such as additional exits and external emergency stairs, to evaluate their effect on congestion. Following a Descriptive-Developmental research design implemented through the V-Model, the system is expected to demonstrate improved evacuation efficiency over static routing and provide the Physical Plant and Facilities Office (PPFO) with a safe, data-driven tool for evaluating evacuation plans and congestion-mitigation strategies.

Keywords: *VR Evacuation Simulation, AI Congestion Prediction, Adaptive Pathfinding*

SECTION I — INTRODUCTION (THE PROBLEM AND ITS SETTING)

1.1 Introduction

School emergencies involving violent attacks often lead to unpredictable evacuation behavior. Panic, congestion, and avoidance of the threat can direct students away from the nearest exits and create dangerous bottlenecks. Existing evacuation systems and building designs are typically evaluated using static routing methods that do not adapt to real-time crowd conditions. This limits their ability to prevent or reduce congestion during an active emergency. The study proposes the development of an AI-assisted, Unity-based virtual reality (VR) evacuation simulator that models student evacuation behavior during a simulated school-shooting emergency at the Systems Plus College Foundation (SPCF) campus. The system integrates a Gated Recurrent Unit (GRU) neural network to predict congestion in critical corridors and exits. It also utilizes the D* Lite adaptive

pathfinding algorithm that reroutes evacuees away from forecasted bottlenecks in real time. The proposed GRU-D* Lite approach will be benchmarked against conventional A* routing across four performance measures: evacuation time, congestion level, route utilization, and evacuation success rate. The study will also test alternative building configurations, such as additional exits and external emergency stairs, to evaluate their effect on congestion. Following a Descriptive-Developmental research design implemented through the V-Model, the system is expected to demonstrate improved evacuation efficiency over static routing and provide the Physical Plant and Facilities Office (PPFO) with a safe, data-driven tool for evaluating evacuation plans and congestion-mitigation strategies.

1.2 Background of the Study

Studies on emergency evacuation show that people do not always choose the nearest exit, as their route choices may be influenced by the conditions and perceived risks during an emergency (Ding et al., 2021). Stress, fear, and the need to avoid threats can also affect evacuation decisions and lead to changes in route selection and crowd distribution (Bahmani et al., 2023). These behaviors can increase congestion, particularly at corridors, corners, and exits, where bottlenecks may reduce evacuation efficiency (Ye et al., 2024; Zhang et al., 2024). VR has therefore been increasingly used to safely study emergency evacuation behavior, including active-shooter scenarios, while recent research highlights the role of panic and crowd dynamics in increasing evacuation time (Liu et al., 2023; Podoletz et al., 2024; Li et al., 2025).

Recent studies are also exploring AI-based approaches for predicting evacuation conditions and improving dynamic path planning (Shi et al., 2025; Sun et al., 2025; Duan et al., 2026). These developments support the integration of VR, AI-based congestion prediction, and adaptive pathfinding to simulate school-shooting emergencies, identify potential bottlenecks, and recommend alternative routes. Such an approach can help improve evacuation efficiency by responding to predicted congestion rather than relying only on fixed evacuation paths.

1. Evacuation Congestion: Students may converge in the same corridors and exits, creating bottlenecks that delay evacuation (Shi et al., 2025).
2. Static Routes: Fixed evacuation routes may continue directing students toward congested areas despite available alternative paths (Venu & Gurusamy, 2025).
3. Limited Prediction: Existing systems may respond only after congestion has already formed because they lack prediction of developing bottlenecks (Liu et al., 2024).
4. Limited Testing of Alternatives: The effectiveness of additional exits, emergency stairs, and alternative routes is difficult to evaluate without testing different building configurations (Zhang et al., 2025).

Existing studies have explored VR-based emergency training, evacuation congestion, AI-based prediction, and adaptive path planning (Liu et al., 2023; Shi et al., 2025). However, these approaches are often studied separately indicating a methodological gap where such methods could be utilized in one study. Although AI can predict evacuation conditions and path-planning methods can adapt to changing environments, limited research combines these approaches into a single VR-based system that predicts congestion, recommends alternative evacuation routes, and evaluates building configurations to minimize congestion during school-shooting emergencies.

1.3 Objectives of the Study

- **General Objective:** Develop an AI-assisted Unity-based VR evacuation simulator that predicts and minimizes pedestrian congestion during simulated school-shooting emergencies through adaptive pathfinding and alternative building configurations.
- **Specific Objectives:**
 1. Develop a Unity-based VR simulation of the SPCF school building and simulate school-shooting evacuation scenarios to generate pedestrian movement and congestion data.

2. Implement a GRU-based congestion prediction model to forecast congestion in critical corridors and exits using simulated pedestrian-movement data.
3. Integrate D* Lite adaptive pathfinding to use predicted congestion in identifying alternative evacuation routes and reducing movement toward congested areas.
4. Examine how alternative building configurations, including additional exits, external emergency stairs, and alternative routes, influence pedestrian congestion during evacuation.
5. Evaluate the performance of the GRU–D* Lite approach and conventional A* routing in terms of evacuation time, congestion level, route utilization, and evacuation success rate.

1.4 Scope and Limitation of the Study

- **Scope:** The study covers the development of a Unity based virtual reality (VR) evacuation simulator integrated with crowd and pedestrian movement simulation to generate synthetic congestion data. It incorporates a Gated Recurrent Unit (GRU) neural network for predictive congestion modeling, D* Lite for adaptive pathfinding, and A* for baseline pathfinding comparison. The evaluation encompasses alternative evacuation routes, additional exits, and external emergency stairs, with performance measured through evacuation time, congestion levels, route utilization, and evacuation success rates. The system is designed to support the Physical Plant and Facilities Office (PPFO) in evaluating spatial configurations and congestion mitigation strategies within the target environment.

The scope is bounded by a single structural model based on the Systems Plus College Foundation (SPCF) College of Computing and Information Sciences (CCIS) building. The VR-based evacuation mechanics simulate general emergency behaviors and do not account for extreme psychological panic or non-standard human responses. Furthermore, the GRU prediction model depends entirely on the volume and variability of the generated training data, while hardware and computational thresholds restrict the maximum density of simulated agents and complex multi-floor configurations.

The simulated shooter is not modeled as an independently adaptive adversarial agent and primarily serves as a factor affecting evacuee route selection. The study focuses only on evacuation and congestion reduction and excludes post-evacuation activities such as first responder coordination, triage, and law enforcement operations. Evaluation is limited to evacuation time, congestion level, route utilization, and evacuation success rate and does not include long-term psychological effects or training transfer.

- **Limitation:** The study may be constrained by several factors beyond the researchers' full control. The VR-based simulation approximates evacuation behavior but may not completely replicate how students would act under actual life-threatening conditions. The accuracy of the GRU congestion-prediction model depends on the volume and variability of the simulated training data. Limited or narrow training scenarios may reduce its predictive reliability in conditions not well represented in that data. Hardware and computational capacity may also constrain the number of simulated agents and the number of building configurations that can be tested within the study period. This may affect the variance of the results and their individual details that could support the prediction analysis.

1.5 Significance of the Study

This study aims to support safer and more efficient school evacuation planning through a VR-based simulation that incorporates congestion prediction and adaptive pathfinding. The study may benefit the following:

School Administrators and Safety Officers. The study may provide a safe virtual environment for evaluating evacuation plans, identifying potential congestion points, and assessing alternative exits and evacuation routes.

Students and School Staff. The study may contribute to safer and more organized evacuation by identifying routes that can help reduce congestion and delays during emergencies.

Architects and Building Designers. The simulation may provide insights into how building layouts, corridors, stairways, and exits influence pedestrian movement and evacuation congestion.

Emergency Responders and Disaster Management Agencies. The study may provide information on potential congestion areas and evacuation patterns that can support emergency response and preparedness planning.

Future Researchers. The study may serve as a reference for future research involving VR-based evacuation simulation, GRU-based congestion prediction, adaptive pathfinding, and AI-assisted emergency planning.

1.6 Definition of Terms

A* Algorithm - A* is a classical pathfinding algorithm that determines the shortest route between two points in a known, static environment based on path cost and heuristic estimation (Venu & Gurusamy, 2025). In this study, A* serves as the baseline routing method against which the GRU-D* Lite approach is benchmarked, representing a fixed, non-adaptive evacuation path that does not respond to real-time congestion changes.

Algorithm - An algorithm is a step-by-step procedure for solving a problem or accomplishing a particular end, especially by a computer (Merriam-Webster, n.d.-a). In this study, algorithm refers specifically to the GRU prediction model and the D* Lite and A* pathfinding procedures used to process congestion data and generate evacuation routes within the simulator.

Benchmark - A benchmark is a standard or point of reference by which something may be measured, judged, or compared (Merriam-Webster, n.d.-b). In this study, benchmarking refers to the comparison of the GRU-D* Lite approach against conventional A* routing, using evacuation time, congestion level, route utilization, and evacuation success rate as the standard metrics of comparison.

Bottleneck - A bottleneck is a narrow passageway, or something that holds up progress (Merriam-Webster, n.d.-c). In this study, a bottleneck refers to a specific corridor, corner, or exit location within the simulated building where predicted or observed congestion exceeds a defined threshold, causing evacuee movement to slow or stall.

Congested - A state of being extremely or excessively full or crowded (Merriam-Webster, n.d.-d). In this study, congestion refers to the density of simulated evacuees accumulating within a defined corridor, exit, or stairway segment at a given time step, used as an input variable for the GRU prediction model and expressed as a congestion level per segment.

D* Lite - D* Lite is an incremental heuristic search algorithm that efficiently updates a previously computed path when environmental conditions change, by reusing prior search results rather than recalculating a route from scratch (Ren et al., 2022). In this study, D* Lite dynamically recalculates evacuation routes for simulated agents based on the GRU model's predicted congestion, rerouting evacuees away from forecasted bottlenecks.

Evacuation Success Rate - A success rate that refers to the proportion of a group that completes a defined process. In this study, evacuation success rate refers to the percentage of simulated evacuee agents who successfully reach a designated exit within the simulation runtime, out of the total number of agents in a given trial.

Gated Recurrent Unit (GRU) - is a recurrent neural network architecture that uses gating mechanisms to regulate the flow of information over time, offering strong time-series prediction accuracy with a simpler structure

than other recurrent models such as LSTM (Hassaan et al., 2025). In this study, the GRU model is the AI component trained on simulated pedestrian-movement data to forecast congestion levels in critical corridors and exits, producing the predictions that inform the D* Lite algorithm's rerouting decisions.

Route Utilization - Utilization refers to the extent to which an available resource or pathway is used relative to its capacity. In this study, route utilization refers to the proportion of simulated evacuees using each available corridor or exit during a trial, indicating whether alternative routes are being effectively distributed rather than concentrated on a single path.

Virtual Reality (VR) - VR is an artificial environment experienced through sensory stimuli provided by a computer, in which a user's actions partially determine what happens within the environment (Merriam-Webster, n.d.-f). In this study, VR refers to the Unity-based simulated 3D replica of an SPCF school building in which agent movement generates the pedestrian and congestion data used to train and test the system.

SECTION II — LITERATURE REVIEW

2.1 Introduction to the Review

This chapter reviews existing research that supports building an emergency evacuation system for school shootings using Unity VR, GRU congestion prediction, and D* Lite route planning. The reviewed studies cover six main topics: how people behave during active attacks, how crowds clog exits and hallways, how virtual reality is used for safety training, how AI models predict traffic and congestion, how dynamic algorithms find safe escape routes in real time, and real-life school shooting cases and emergency planning in the Philippines.

Together, these studies highlight a key gap in current research: while many tools focus on individual parts of an emergency, few combine live AI congestion forecasting with dynamic rerouting inside a VR school environment. Looking at these different areas helps show why an integrated system is needed to help students find safer paths and avoid dangerous crowds during a campus threat.

2.2 Review of Related Literature and Studies

2.2.1 Evacuation Congestion and Building Design

Studies show that congestion is strongly affected by exit design, building layout, crowd size, and human behavior. Ye et al. (2024) found that crowd size, entry flow, and exit width influence arch-shaped congestion at building exits. Lu et al. (2024) showed that corner design and walking speed affect crowd flow and shockwave formation in narrow passages. Shi et al. (2025) found that exit location and width influence evacuation efficiency at bottlenecks during floods. Zhang et al. (2025) demonstrated that machine learning can predict congestion and help improve university library evacuation design. Liu et al. (2024) showed that neural networks can accurately predict evacuation travel time under different staircase congestion levels. Wei et al. (2024) found that risk-averse route choices reduced evacuation time by 12.07% to 28.84%.

2.2.2 Evacuation During School Shootings and Violent Attacks

Ding et al. (2021) found that classroom attacks caused delayed reactions, changing exit choices, and high crowd density between seats and aisles. Yang and Ding (2023) used machine learning to predict evacuation success based on factors such as distance from the attacker and preparation time. Wang et al. (2024) showed that emotions and panic can affect evacuation time and casualties during violent attacks. Guo et al. (2024) found that excessive panic, larger groups, and multiple attackers increased evacuation delays and deaths. Duan et al. (2026) used deep reinforcement learning to control crowd congestion during terrorist attacks. McClurg and Wagner (2025) demonstrated that VR can safely collect realistic information about school-shooter movements.

Liu et al. (2024) found that providing more exits improved evacuation and reduced harm, especially when exits were located near the attacker's starting position.

2.2.3 Virtual Reality and Unity-Based Emergency Simulation

Virtual environments allow researchers to study dangerous emergencies without exposing participants to real harm. Liu et al. (2023) found that interactive VR training improved active-shooter response and preparedness more effectively than video-based training. Podoletz et al. (2024) reported that VR and XR can provide flexible and immersive police training but may create concerns involving realism, trauma, privacy, and safety. Wächter et al. (2022) showed that Unity-based dynamic guidance helped users avoid temporary hazards more efficiently than static exit signs. Huang et al. (2023) demonstrated that Unity, agent-based modeling, BIM, and A* could simulate dormitory evacuation and identify delays that create choke points.

2.2.4 Artificial Intelligence for Prediction and Crowd Coordination

Artificial intelligence can process changing evacuation conditions and support faster decisions. Hassaan et al. (2025) found that GRU provided strong time-series prediction accuracy while using a simpler structure than other recurrent models. Sun et al. (2025) showed that a GRU-based multi-agent system improved route coordination, exit use, collision avoidance, and evacuation efficiency. Silinskaya et al. (2025) found that MAPPO-based group evacuation reduced total evacuation time by about 38%, while four to six leaders helped lower panic and collisions.

2.2.5 Dynamic and Adaptive Pathfinding

Dynamic pathfinding studies support the use of D* Lite when routes or obstacles change during an emergency. Ren et al. (2022) showed that multi-objective D* Lite could reuse earlier search results and efficiently update paths when conditions changed. Venu and Gurusamy (2025) explained that classical algorithms work well in known environments, while AI and hybrid methods provide better adaptation in dynamic environments. Tao and Kim (2024) found that deep reinforcement learning improved navigation speed, path smoothness, and obstacle avoidance in changing environments. Li et al. (2024) improved D* Lite to generate safer and smoother paths while responding to moving obstacles. Jin et al. (2023) reported that conflict-based D* Lite improved pathfinding success by about 31% in a dynamic test map. Yao et al. (2025) showed that combining A*, D* Lite, obstacle prediction, and bat clustering reduced travel paths and rescue time.

2.2.6 Philippine and Local Evacuation Context

Philippine studies and reports show the importance of evacuation planning under local building, capacity, and emergency conditions. Barbosa et al. (2024) used 3D GIS and agent-based simulation to identify evacuation delays and underused exits at a University of the Philippines residence hall. Lim et al. (2025) used cellular automata at Philippine Science High School–Main Campus to compare evacuation time and travel distance under different starting arrangements. Rico et al. (2024) developed a model for selecting safer and more accessible evacuation centers in Taguig City. Panonce (2024) found that teachers experienced safety concerns, emotional strain, disruption, and adaptation when their school served as an evacuation center. Caliwán (2026) reported a fatal campus shooting in Zamboanga, showing that armed threats can occur in Philippine schools. The Associated Press (2026) reported that students were injured while escaping a shooting at a public high school in Tacloban. The Philippine News Agency (2023) also provided national context on the need for coordinated emergency preparedness and response. Together, these studies provide the foundation for examining how VR simulation, congestion prediction, and adaptive pathfinding can improve school evacuation planning during shooting emergencies.

2.3 Conceptual Framework

With the review of related literature, the variables are illustrated in an Input, Process, Output Model as a proposed AI-assisted evacuation solution concept. The framework also integrates Unity-based Virtual Reality

simulation, Gated Recurrent Unit congestion prediction, D* Lite adaptive pathfinding, and an existing conventional A* pathfinding data to be evaluated with the output of the proposed model.

Figure 1
Conceptual Framework

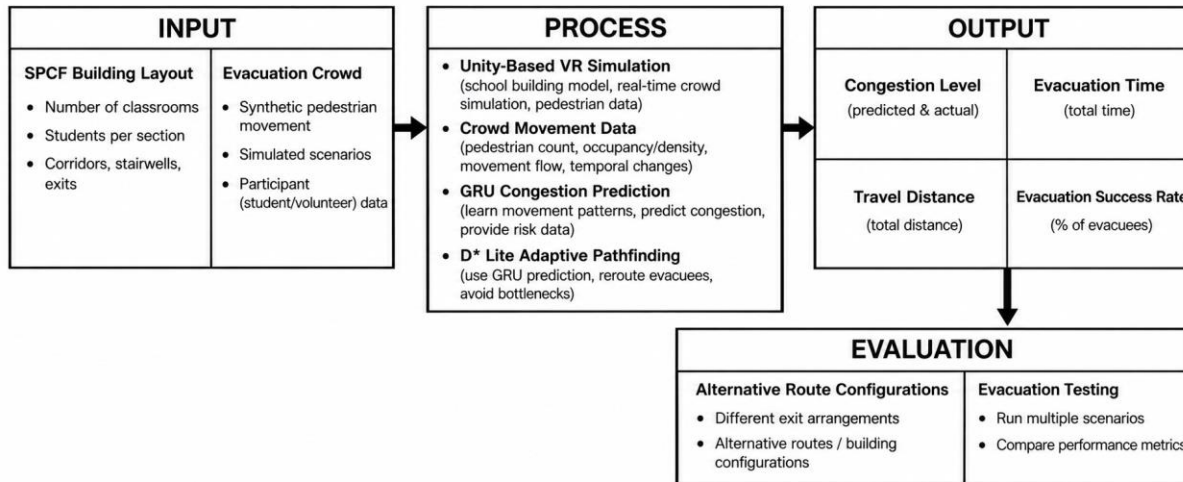


Figure 1 shows the conceptual framework highlighting the input, process, output, and the evaluation of the proposed system. The input consists of the physical and simulated conditions required for the evacuation system. These include the SPCF building layout, classrooms, corridors, stairways, existing exits, pedestrian population, pedestrian movement, crowd density, and simulated emergency conditions. The other half comprises the alternative building configurations to examine their effects on the congestion and how it is impacted. These inputs provide the environmental movement data necessary for data collection to be processed.

The process begins with the development of a Unity-based VR representation of the SPCF school building. Simulated school-shooting evacuation scenarios are conducted within the virtual environment to generate pedestrian-movement and congestion data. The generated data are then processed using a GRU-based congestion prediction model to forecast congestion in critical corridors and exits. The predicted congestion information is subsequently incorporated into D Lite adaptive pathfinding*, allowing the system to identify alternative routes when congestion or other route conditions change. This process aims to reduce pedestrian movement toward highly congested areas.

After the simulation and evaluation of their effects, the output consists of the resulting evacuation performance data and the developed AI-assisted Unity-based VR evacuation simulator. The system produces predicted congestion conditions, adaptive evacuation routes, and comparative performance results for different building configurations and routing approaches. The resulting information can support evaluating potential congestion-mitigation strategies and examining evacuation planning alternatives within the simulated school environment.

2.4 Synthesis

The reviewed literature shows that crowd density, panic, exit availability, building layout, and attacker location can strongly affect evacuation safety. Studies on building design demonstrate that wider and properly located exits can reduce congestion, while research on violent attacks shows that fear, attacker movement, and

perceived danger can change people's route choices. These findings support the need to model both physical bottlenecks and threat-related behavior during school-shooting evacuations.

Studies involving VR and Unity show that dangerous emergency situations can be simulated without exposing participants to actual harm. Artificial intelligence studies also demonstrate that GRU and other learning models can predict changing conditions and coordinate crowd movement. Research on D* Lite further shows that routes can be updated when obstacles or environmental conditions change. However, these technologies are commonly studied separately or applied to fires, floods, robot navigation, and general building evacuation.

Philippine studies support the use of simulation and optimization for evacuation planning in schools and local communities. Local reports of school shootings also show that armed threats can occur in Philippine educational institutions. However, the reviewed Philippine studies do not examine indoor congestion during school-shooting emergencies or use AI to provide adaptive evacuation routes.

Overall, no reviewed study combines a Unity-based VR school-shooting simulation, GRU congestion prediction, and D* Lite adaptive pathfinding in one system. Existing studies also do not compare static A* routing with adaptive D* Lite routing while testing building improvements such as additional exits and external emergency stairs. The proposed study addresses this gap by developing an AI-assisted VR simulator that predicts congestion, adjusts evacuation routes, and evaluates building changes intended to reduce bottlenecks during school-shooting emergencies.

SECTION III — METHODOLOGY

3.1 Research Design

This study employs a Descriptive-Developmental Research Design with a Quantitative Approach. The developmental aspect guides the design and development of the Unity-based VR evacuation simulator, including the crowd simulation, GRU congestion prediction, A* baseline routing, and D* Lite adaptive pathfinding. The descriptive-quantitative aspect evaluates the system's performance by comparing evacuation time, congestion level, route utilization, and evacuation success rate across different routing methods and building configurations. The study will also gather quantitative user-evaluation data from selected PPFO personnel using a 5-point Likert-scale questionnaire based on selected ISO/IEC 25010 software-quality characteristics.

3.2 System Development Methodology

The researchers will use the V-Model to develop and test the proposed system. The V-Model connects each development stage with a matching testing stage. The left side focuses on planning and design, while the right side focuses on testing the finished parts of the system.

The V-Model is suitable for this study because the system has several parts that must work together. These include the Unity VR environment, crowd simulation, GRU congestion prediction, A* routing, D* Lite routing, and data-recording functions. Each part will be planned, developed, and tested based on the requirements of the study.

The system will follow these stages:

1. Requirements Analysis

The researchers will identify what the system needs to do. The system must create a virtual school environment, simulate crowd movement, predict congestion, generate evacuation routes, and record simulation results.

The researchers will also identify the needed hardware, software, school-layout data, crowd settings, and evaluation measures. These requirements will serve as the basis for user acceptance testing.

2. System Design

The researchers will design how the complete system will work. This stage will show how Unity, the simulated agents, the GRU model, A*, D* Lite, and the data-recording functions will connect.

The researchers will also identify the system inputs and outputs. Inputs may include the school layout, crowd size, agent starting locations, available exits, and selected routing method. Outputs may include evacuation time, congestion level, crowd density, exit throughput, bottleneck duration, route length, and predicted congestion. The complete system design will serve as the basis for system testing.

3. Architectural Design

The system will be divided into its main parts. These will include the following:

1. Unity VR environment
2. Crowd simulation
3. Congestion-data collection
4. GRU prediction model
5. A* routing
6. D* Lite routing
7. Scenario controls
8. Results recording

The researchers will identify how these parts will share information. For example, the crowd simulation will produce movement and congestion data. The GRU model will use the data to predict possible congestion. D* Lite will use the updated conditions to find another evacuation route when the current route becomes crowded or unsafe. The connections between these parts will be checked during integration testing.

4. Module Design

The researchers will prepare the detailed design of each system part. The Unity environment will include classrooms, corridors, stairs, exits, safe areas, and possible bottleneck locations.

The crowd simulation will define the starting positions, movement speed, behavior, route selection, and destinations of the agents. The GRU design will identify its input data, training process, and expected prediction output.

The A* module will calculate the initial evacuation routes. The D* Lite module will update the routes when congestion, obstacles, or unsafe conditions are detected. Each module will be checked during unit testing.

5. System Development

The researchers will build the system based on the approved designs. The virtual school and crowd simulation will be created in Unity.

A* will serve as the baseline routing method. D* Lite will serve as the adaptive routing method. The researchers will also prepare the simulation data, train the GRU model, and connect it to the Unity system.

After the parts are developed, they will be combined into one working VR evacuation simulator.

6. Unit Testing

Each part of the system will be tested separately. The researchers will test the Unity environment, agent movement, collision handling, exit detection, congestion recording, GRU prediction, A* routing, D* Lite route updating, scenario controls, and results recording.

The predicted congestion from the GRU model will be compared with the actual congestion recorded during the simulation. Any part that does not produce the expected result will be corrected and tested again.

7. Integration Testing

Integration testing will check whether the different parts work correctly when connected. The researchers will check whether Unity can send crowd data to the GRU model. They will also check whether the routing system receives the congestion prediction and whether D* Lite updates the routes when conditions change.

Problems involving data transfer, timing, or connections between the system parts will be corrected before system testing.

8. System Testing

The researchers will test the complete system based on the requirements and system design. Controlled simulation runs will compare A* with D* Lite. Both routing methods will be tested using the same crowd size, starting positions, movement settings, exits, and building layout.

The researchers will compare the evacuation time, congestion level, crowd density, bottleneck duration, exit throughput, and route length produced by each routing method. They will also test building changes, such as adding exits or external emergency stairs, to determine whether these changes reduce congestion.

9. User Acceptance Testing

Students and school staff will evaluate the completed system. They will answer a structured Likert-scale questionnaire based on selected ISO/IEC 25010 software-quality characteristics.

The questionnaire will measure the system's functional suitability, usability, reliability, and performance efficiency. The study will use purposive sampling because the participants will be selected based on their connection to the intended users of the system.

The final number of participants will follow the recommendation and approval of the research adviser, school administration, or research ethics committee.

Some student participants may be minors. Because of this, the researchers will first obtain approval from the proper institution. They will also obtain consent from the student's parent or guardian and assent from the student.

Participation will be voluntary. Participants may stop at any time without receiving a penalty. The VR simulation will not include unnecessary graphic violence. Participants will receive a content warning, safety instructions, and a clear option to stop the simulation if they feel uncomfortable, afraid, dizzy, or unwell. The researchers will also conduct a short debriefing after the activity.

The questionnaire results and simulation results will be analyzed separately. The questionnaire will show how the students and staff rate the system. The simulation data will show the performance of the GRU model, A*, D* Lite, and the tested building changes.

In the V-Model, every development stage has a matching testing stage. User acceptance testing checks the requirements. System testing checks the complete system design. Integration testing checks whether the main parts work together. Unit testing checks each individual module. This process will help the researchers confirm that the system works as planned and meets the objectives of the study.

3.3 Requirement Specification and Analysis

This section identifies the functions and requirements of the proposed AI-assisted VR evacuation simulator. The requirements were based on the objectives of the study and the expected operation of the system.

The proposed system will create a virtual school environment, simulate crowd movement during a school-shooting emergency, predict congestion through a GRU model, and generate evacuation routes using A* and D* Lite. It will also allow the researchers to test changes to the school layout, such as adding exits or external emergency stairs.

3.3.1 Functional Requirements

Functional requirements describe the actions that the system must perform.

1. School Environment Creation

The system must provide a virtual school environment containing classrooms, corridors, stairs, exits, safe areas, and possible bottleneck locations.

2. Scenario Configuration

The researchers must be able to set the crowd size, agent starting positions, available exits, threat location, blocked paths, routing method, and building layout before starting a simulation.

3. Crowd Simulation

The system must simulate the movement of agents from their starting locations to available exits or safe areas.

4. A* Route Generation

The system must use A* as the baseline routing method. It must generate an initial path from each agent's location to an available exit.

5. Congestion Data Collection

The system must collect movement and congestion data during the simulation. These data may include crowd density, movement speed, waiting time, exit use, and bottleneck duration.

6. GRU Congestion Prediction

The system must use the trained GRU model to predict possible congestion in corridors, stairs, and exits.

7. D* Lite Route Updating

The system must use D* Lite to update evacuation routes when congestion, blocked paths, or unsafe areas are detected.

8. Building Layout Testing

The researchers must be able to test the original school layout and proposed changes, such as additional exits, wider passages, or external emergency stairs.

9. Simulation Data Recording

The system must record the settings and results of every simulation. The recorded data must include the routing method, evacuation time, congestion measurements, exit use, and route length.

10. Result Comparison

The system must support the comparison of A* and D* Lite. It must also compare the results of the original school layout with the proposed building changes.

11. Result Presentation

The system must present the results in a clear form. Results may be displayed through route views, congestion indicators, summaries, graphs, or exported data files.

12. User Evaluation

The completed VR simulator must be available for evaluation by selected students and school staff. Their responses will be collected through a structured questionnaire.

3.3.2 Nonfunctional Requirements

Nonfunctional requirements describe how the system should perform.

1. Usability

The controls, labels, instructions, and settings must be easy to understand. Users must be able to start, stop, and exit the simulation without difficulty.

2. Performance Efficiency

The system must process crowd movement, congestion prediction, and route updates without delays that interrupt the simulation.

3. Reliability

The system must record the required data correctly. It must also produce consistent results when the same settings and conditions are used.

4. Accuracy

The GRU predictions must be compared with the actual congestion recorded during the simulation. Routes created by A* and D* Lite must lead agents toward valid exits.

5. Compatibility

The system must work with the computer and VR equipment selected for the study. Unity, the GRU model, and the routing components must be able to exchange the required data.

6. Safety

The VR simulation must avoid unnecessary graphic violence. Users must be able to stop the simulation immediately if they feel afraid, uncomfortable, dizzy, or unwell.

7. Data Protection

Participant responses and simulation records must be stored securely. The presented results must not reveal the identity of any participant.

8. Maintainability

The system must allow the researchers to update the school layout, crowd settings, GRU model, and routing functions when corrections are needed.

3.3.3 Level 0 Data Flow Diagram

The Level 0 Data Flow Diagram presents the proposed system as one main process. It shows the basic exchange of information between the researchers and the AI-assisted VR evacuation simulator.

Figure 2

Data Flow Diagram

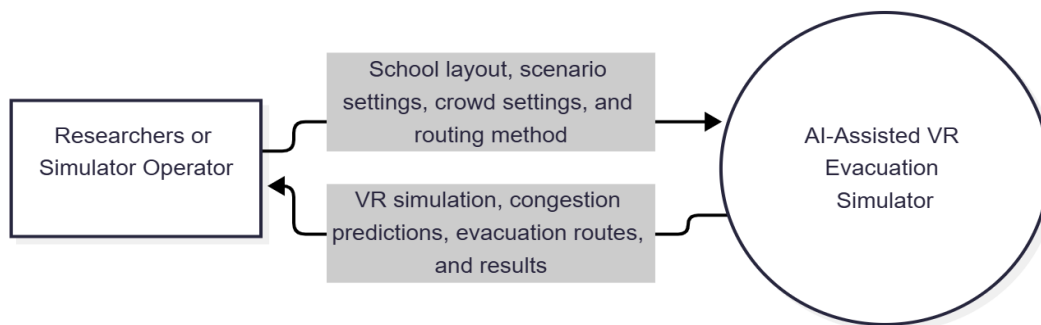


Figure 2 shows the main flow of data between the researchers and the proposed system. The researchers provide the school layout, scenario settings, crowd settings, and selected routing method. The system processes these inputs and produces the VR simulation, congestion predictions, evacuation routes, and simulation results.

3.3.4 Level 1 Data Flow Diagram

The Level 1 Data Flow Diagram divides the proposed system into its main processes. It provides a more detailed view of how the system receives, processes, stores, and presents information.

Figure 3

Level 1 Data Flow Diagram

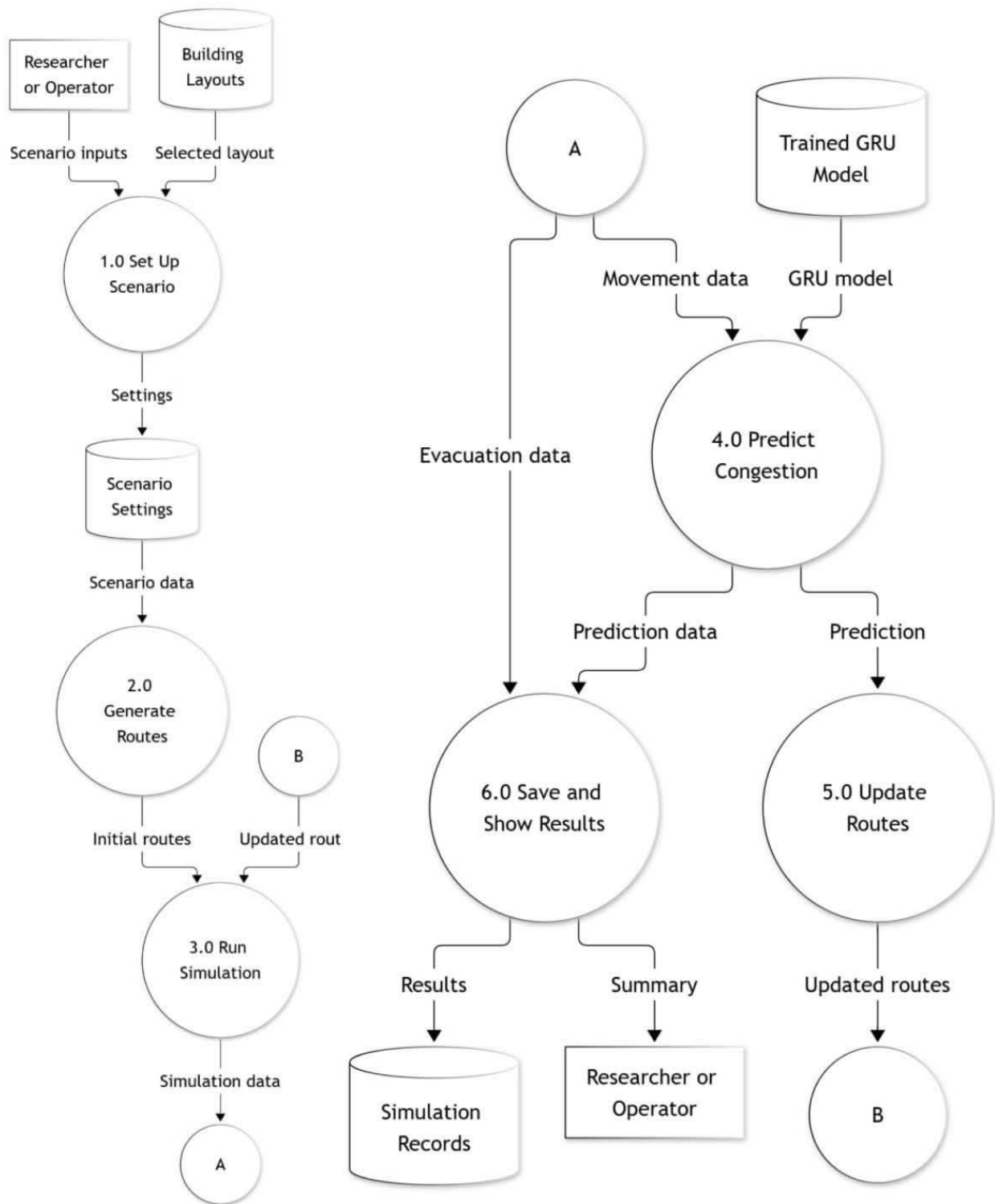


Figure 3 shows the main processes of the proposed system. The researchers first set up the simulation scenario and select a building layout. The system then generates the initial routes and runs the crowd simulation. Movement data is processed by the GRU model to predict congestion. When D* Lite is selected, the system updates the evacuation routes based on the predicted conditions. The simulation and prediction results are then recorded and presented to the researchers.

3.3.5 System Flowchart

The system flowchart shows the order of activities performed by the proposed simulator. It covers the process from loading the school layout to recording and presenting the results.

Figure 4

System Flowchart

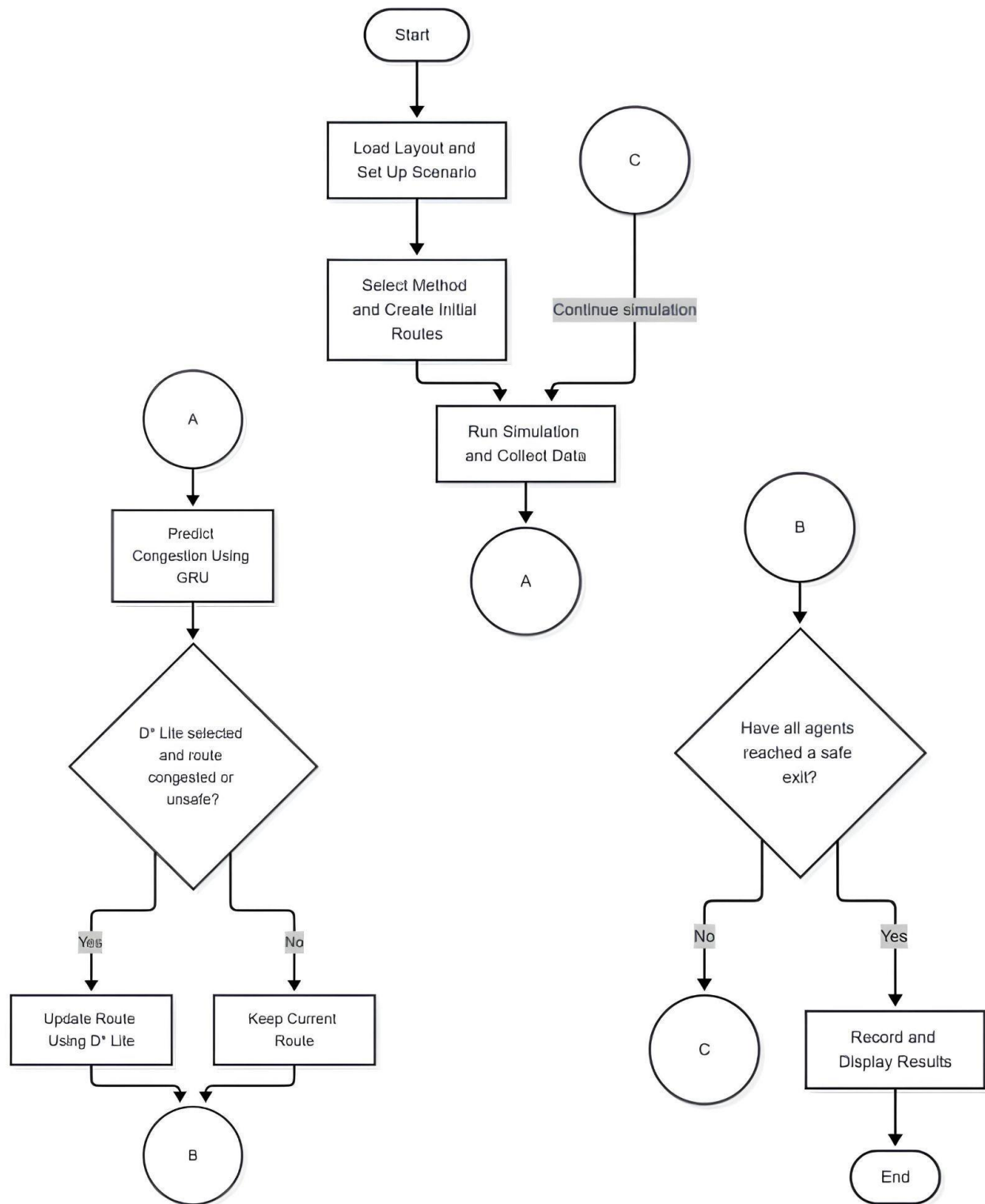


Figure 4 shows the main flow of the evacuation simulation. The researchers first load the school layout, configure the scenario, and select a routing method. The system creates the agents and generates their initial routes before starting the simulation. The GRU model uses the collected movement data to predict congestion.

If D* Lite is selected, the route is updated when congestion or an unsafe path is detected. The process continues until all agents reach a safe exit. The system then records and displays the results. .

3.3.6 Entity-Relationship Diagram

The Entity-Relationship Diagram shows how the main data groups of the proposed system are connected. It provides a guide for organizing the information recorded during each simulation.

Figure 5
Entity Relationship Diagram

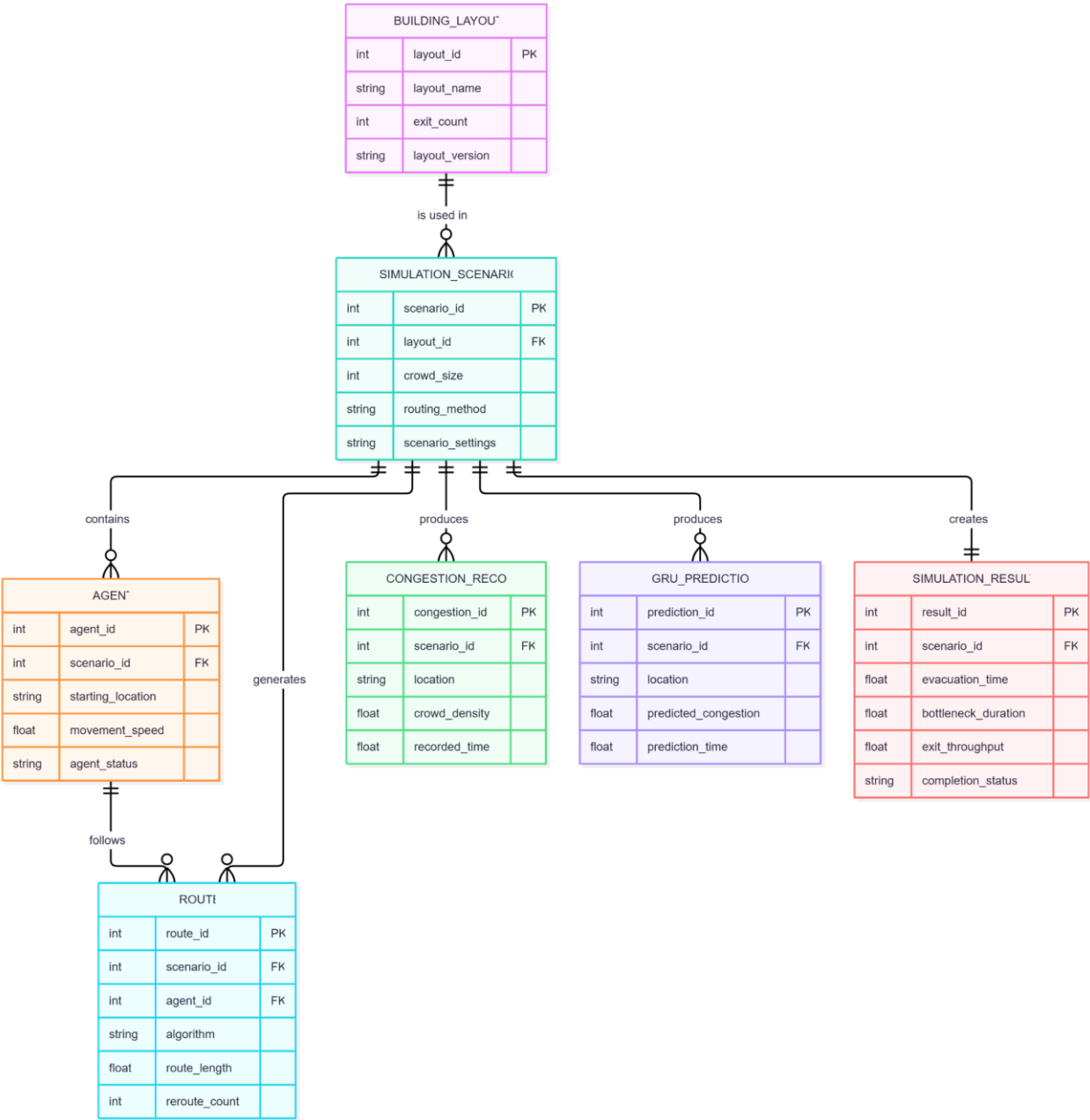


Figure 5 shows the relationship among the building layout, simulation scenario, agents, routes, congestion records, GRU predictions, and simulation results. A building layout may be used in several simulation scenarios. Each scenario may contain several agents and routes. It may also produce several congestion records and GRU predictions.

Each completed scenario produces a simulation result containing measurements such as evacuation time, bottleneck duration, exit throughput, and completion status. These records will support the comparison of routing methods and building layouts.

The functional requirements, nonfunctional requirements, and system diagrams will guide the development and testing of the proposed simulator. They will also help the researchers check whether the final system meets the objectives of the study.

3.4 System Design Specification

- **Logical Specification:** The system will provide a user interface for the Physical Plant and Facilities Office (PPFO) to configure the school layout, evacuation scenario, crowd settings, available exits, blocked paths, and routing method. The interface will also provide controls for starting and stopping simulations and displaying evacuation routes, congestion predictions, and simulation results. The system modules will include the Unity VR environment, crowd simulation, congestion-data collection, GRU congestion prediction, A* baseline routing, D* Lite adaptive routing, scenario configuration, and results recording. The module logic will allow pedestrian-movement data to be collected and processed by the GRU model, while predicted congestion will be used by D* Lite to update evacuation routes when necessary.

- **Physical Specification:** The system will use Unity as the primary development platform for the VR environment and crowd simulation, with a GRU-based neural network for congestion prediction, A* for baseline pathfinding, and D Lite* for adaptive pathfinding. The system will operate on a computer connected to compatible VR equipment and will use data storage for school layouts, simulation scenarios, pedestrian-movement data, congestion records, GRU predictions, routing results, and simulation measurements. The physical setup will consist of the computer running the simulator and AI components, compatible VR equipment for immersive simulation, and local storage for the generated simulation and evaluation records.

3.5 Implementation

The system will be implemented in Unity following the designed modules and system flow. The Physical Plant and Facilities Office (PPFO) will configure evacuation scenarios and building layouts, while the crowd simulation will generate pedestrian movement and congestion data. The collected data will be used to train and test the GRU congestion prediction model. A* will generate baseline evacuation routes, while D* Lite will update routes based on predicted congestion and changing conditions. The system components will then be integrated to allow simulation, congestion prediction, adaptive routing, and recording of results. Alternative configurations, such as additional exits, external emergency stairs, and modified evacuation routes, will also be implemented for congestion-mitigation testing.

3.6 Testing and Evaluation

The system will be evaluated through Unit Testing, Integration Testing, System Testing, and User Acceptance Testing (UAT). Unit testing will verify individual modules, while integration testing will check the connections between Unity, the GRU model, A*, D* Lite, and the data-recording functions. System testing will compare A* and D* Lite using controlled evacuation scenarios and test alternative building configurations. Performance will

be measured using evacuation time, congestion level, route utilization, and evacuation success rate. UAT will involve selected PPFO personnel and will use a 5-point Likert-scale questionnaire based on selected ISO/IEC 25010 quality characteristics, particularly functional suitability, usability, reliability, and performance efficiency.

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