Enhancing Emergency Preparedness in Mass Gatherings through Crowd Simulation and Cascading Effect Analysis

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ABSTRACT

In collaboration with French firefighters (SDIS 62), this study aims to enhance emergency preparedness for mass gatherings through a comprehensive framework integrating crowd simulation and cascading effect analysis. The proposed framework enables the modeling of various emergency scenarios and the evaluation of potential response strategies. The framework's application is demonstrated through a case study of a major music festival. Furthermore, a proposed simulation of high-urgency medical scenarios using what-if analyses is explored to optimize response times. The integration of advanced communication technologies, such as drones and telemedicine, is highlighted for its potential to transform emergency response effectiveness. The findings of the study imply that such a framework can refine proactive planning for large-scale events and improve overall readiness to respond to emergencies.

Keywords

Emergency preparedness, mass gatherings, crowd simulation, cascading effect, communication technology.

1. INTRODUCTION

Mass gatherings, defined by the World Health Organization as events that strain the planning and response resources of the host community (World Health Organization, 2019), pose unique challenges to emergency preparedness. The high density of people in such settings can rapidly escalate minor incidents into major emergencies, requiring proactive planning to ensure safety and manage potential risks (Soomaroo & Murray, 2012). Effective preparedness involves a multifaceted approach encompassing risk assessment, resource allocation, communication planning, and coordination with authorities (Herstein et al., 2021). This continuous process relies heavily on performance measurement and corrective action to ensure readiness for various emergency types (Nelson et al., 2007).

Crowd simulation techniques have been widely adopted for emergency preparedness, aiming to predict and analyze crowd dynamics to enhance safety, optimize crowd management, and improve emergency response strategies (Helbing et al., 2000; Oğuz et al., 2010). The relevance of crowd simulation has grown significantly in recent years due to the increasing frequency and scale of mass gatherings, such as religious pilgrimages, sporting events, and political rallies. Recent advancements in crowd dynamics have leveraged agent-based models (ABMs) to simulate the complex dynamics of large-scale evacuations. Mahmood et al. (2017) proposed an ABM framework to simulate high-density crowds in emergency evacuation scenarios. Sharma and Ali (2022) developed a VR-based simulation for active shooter scenarios and demonstrated the use of behavior trees to model complex evacuation behaviors. In the context of large-scale event crowd control, Aros-Vera et al. (2020) introduced a simulation-based framework to assess the capacity of checkpoints and attendee regulations in crowd management. Additionally, Yasufuku and Takahashi (2024) developed a real-time crowd flow prediction and visualization platform for managing large-scale events.

Despite significant advancements in the field, several areas in emergency preparedness for mass gatherings could benefit from further exploration. First, existing research often lacks the integration of cascading effects simulation and analysis. Historical evidence shows that the high density of attendees in mass gatherings can rapidly escalate minor incidents into major emergencies (Helbing et al., 2000; Soomaroo & Murra, 2012). Recognizing how an initial incident can lead to subsequent emergencies merits more attention for comprehensive preparedness. Second, while crowd simulation techniques are well-established for analyzing large-scale safety and evacuation patterns, there is a gap in modeling the specific response processes for high-urgency medical events where initiating treatment within the “Golden Hour” is critical (Saver et al., 2010). Third, although advanced communication technologies such as drones and telemedicine systems are increasingly adopted for large-scale events (Lafortune et al., 2023), the simulation-based evaluation of their specific impact on compressing emergency response timelines remains to be explored.

The main objective of this paper is to introduce a framework that integrates crowd simulation and cascading effect analysis to enhance emergency preparedness and proactive planning for mass gatherings. This framework’s practical application is demonstrated through a case study of a major music festival. Using the AnyLogic© simulation tool and its pedestrian library, we have simulated crowd movement and low-urgency medical emergencies. Additionally, the paper details a proposal for simulating high-urgency medical emergencies, presenting a set of what-if scenarios to identify optimal strategies for minimizing response time and improving patient outcomes.

The remainder of the paper is organized as follows. In Section 2, the research framework for emergency preparedness is presented. Section 3 explores the simulation of crowd movement and medical emergencies through a use case. Section 4 discusses the practicality of communication protocols in enhancing emergency detection, following with a conclusion in Section 5.

2. RESEARCH FRAMEWORK

The proposed framework aims to enhance emergency preparedness by (i.) generating what-if scenarios based on potential risks and opportunities; (ii.) modeling and assessing these scenarios through simulation techniques; (ii.) providing decision support through a performance comparison dashboard. This framework unfolds two layers.

As shown in Figure 1, the first layer, **modeling and assessment**, focuses on understanding the dynamics of emergency situations. It serves as the analytical core of the framework that maps simulated scenarios into immediate and secondary impacts through performance evaluation.

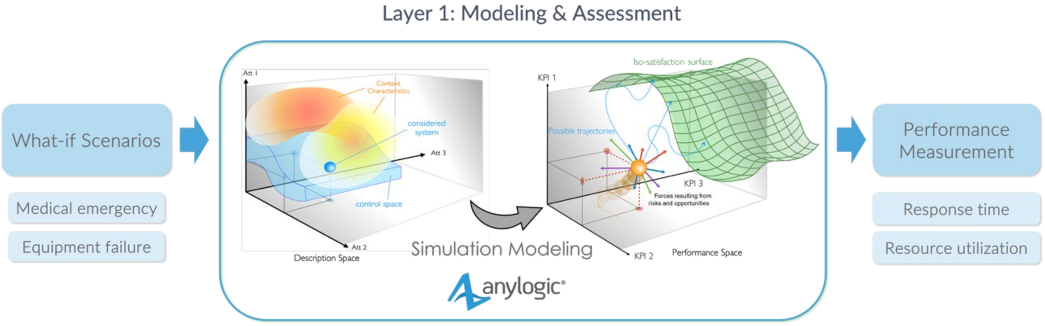


Figure 1. Modeling and assessment layer of the proposed framework

More specifically, this layer cores around the projection of what-if scenarios for emergency preparedness and response. Hypothetical situations are created to envision specific incidents such as medical emergencies, terrorist attacks, analyze how these incidents could unfold, and assess the potential outcomes and impacts of different courses of action (Rome et al., 2016). To realize, simulation modeling methods such as agent-based modeling and discrete-event simulation are employed to test projected scenarios and evaluate the effectiveness of different response plans. The output includes a set of performance metrics such as response time and resource utilization, for each alternative response plan. These metrics provide a quantitative basis for assessing and comparing different plans under various scenarios.

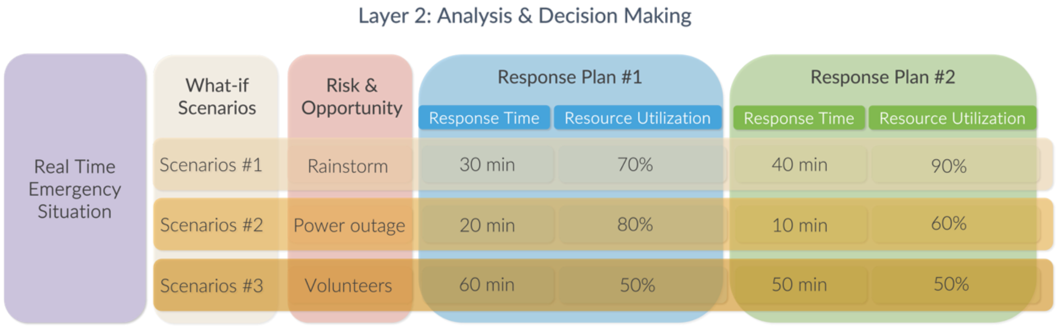
As shown in Figure 2, the second layer, **analysis and decision-making**, focuses on transforming simulation outputs into actionable insights that enable informed decisions for developing adaptive emergency response strategies. By incorporating the detailed results obtained from the first layer, a decision support dashboard can be designed for a comprehensive comparison of different emergency response strategies. Decision-makers can quickly assess how each response plan performs under various scenarios, considering the identified risks and opportunities. More specifically, two objectives are expected on the dashboard:

(i.) Identification of critical thresholds where emergency responses might be overwhelmed.

By simulating a wide range of what-if scenarios, the first layer helps in understanding different conditions under which responses are tested. This includes scenarios with high crowd densities, multiple simultaneous incidents, or delayed emergency responses. The generated metrics enable to pinpoint scenarios where the demand for emergency assistance exceeds the available capacity. Besides, by pushing the simulations to extreme conditions, the breaking points of the system can be identified, that is the thresholds where medical responses fail to keep up with the demands.

(ii.) Optimization of resource allocation to improve response times.

The first layer's simulations provide detailed insights into how different resources (e.g., security and medical staff) are utilized during various scenarios. This helps in identifying inefficiencies and areas where resources can be better allocated. Furthermore, by analyzing response times under different conditions, the simulation helps to identify the fastest routes, optimal positioning of resources, and the best strategies for quick deployment.



Real Time Emergency Situation	What-if Scenarios	Risk & Opportunity	Response Plan #1 Response Time	Response Plan #1 Resource Utilization	Response Plan #2 Response Time	Response Plan #2 Resource Utilization
Real Time Emergency Situation	Scenarios #1	Rainstorm	30 min	70%	40 min	90%
	Scenarios #2	Power outage	20 min	80%	10 min	60%
	Scenarios #3	Volunteers	60 min	50%	50 min	50%

Figure 2. Analysis and decision-making layer of the proposed framework

3. CROWD SIMULATION AND ANALYSIS IN MASS GATHERINGS

Mass gatherings, where large numbers of people assemble for a common purpose, present unique challenges in safety and emergency preparedness. The massive flow of attendees can create a complex situation that requires thorough planning and operational support for public safety and security (Mahmood et al., 2017). Aiming to enhance situational awareness for event organizers and government agencies, a practical use-case of our framework is demonstrated in the context of a major music festival held on the former Cambrai-Epinoy Air Base, France, which hosts between 20,000 and 30,000 attendees.

We have developed a crowd simulation model in mass gatherings based on agent-based modeling. This crowd simulation serves two objectives: (i.) modeling and visualizing crowd flows within the confined environment; (ii.) anticipating the impacts of current and future risks, including cascading effects on both the crowd and emergency responses.

3.1. Simulation of Crowd Movements

3.1.1. Methodology

The simulation modeling of crowd movements in mass gatherings involves a structured approach comprising three main steps:

- First, attendees are modeled as agents within a real-scale environment to accurately represent the event setting. They are assigned characteristics and movement behaviors to reflect realistic crowd dynamics.
- Second, the normal movements of the crowd within these modeled environments are simulated, which

capture typical crowd flow patterns.
- Third, emergency scenarios are introduced to the simulation to analyze crowd responses under stress. In this article, we specifically simulate medical emergencies.

To implement these steps, the simulation tool AnyLogic© and its pedestrian library are adopted. The pedestrian library is dedicated to simulating pedestrian flows in physical environments. It replicates detailed and realistic crowd behavior by incorporating factors such as walking speed, space preferences, and behavioral reactions to different stimuli.

3.1.2. Modeling of Environment and Crowd Movements

Figure 3 presents the layout of the festival zone in the Cambrai-Epinoy Air Base provided by SDIS 62. The environment is modeled to represent the structure. Key areas include: outside queue, entrance and exit, ticket-check area, waiting area, stage area, emergency-aid area, and emergency exit.

Figure 3. Layout of the festival zone in the Cambrai-Epinoy Air Base

The pedestrian library supports the modeling and visualization of the crowd movement process. It allows for the detailed representation of crowd behaviors and interactions. Within the environment, the crowd movement process is further modeled and visualized as follows:

- The simulation begins as attendees line up outside the venue, preparing to enter.
- Attendees enter through the main entrance and proceed to the ticket-check area.
- After ticket checking, attendees either stay in the waiting area or move directly to the stage area, depending on their preferences.
- At any point after ticket checking and during the event, some attendees may feel unwell and move to the emergency-aid area for medical assistance.
- After receiving first aid, some attendees may return to the event if their condition allows. Those requiring further medical treatment are transported to the hospital via the emergency exit.

Additionally, the library offers functionality for 3D visualization by putting cameras in different locations on the layout. This capability allows observers to track attendees' flow and monitor the crowd density from multiple perspectives, as shown in Figure 4.

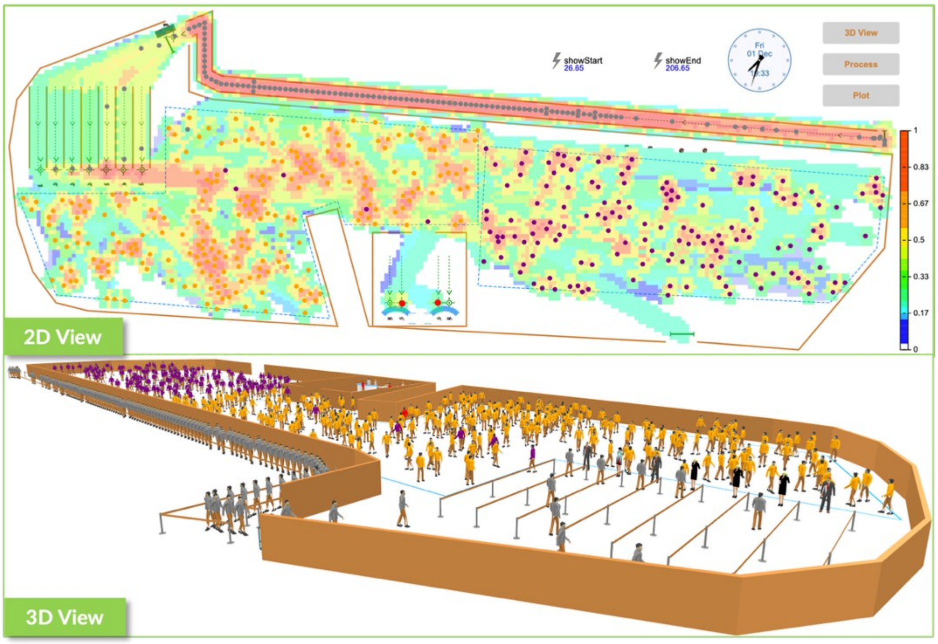


Figure 4. 2D and 3D outputs of crowd movement modeled by Anylogic

3.1.3. Preliminary Results and Metrics

As the simulation proceeds, we utilized various charts to visualize key performance indicators, which provide crucial insights into the crowd's behavior and emergency response effectiveness. To demonstrate the framework's functionality, a baseline simulation of the music festival use-case was conducted. The following metrics, visualized in Figure 5, represent actual outputs from an initial simulation run using a crowd size of approximately 20,000 agents.

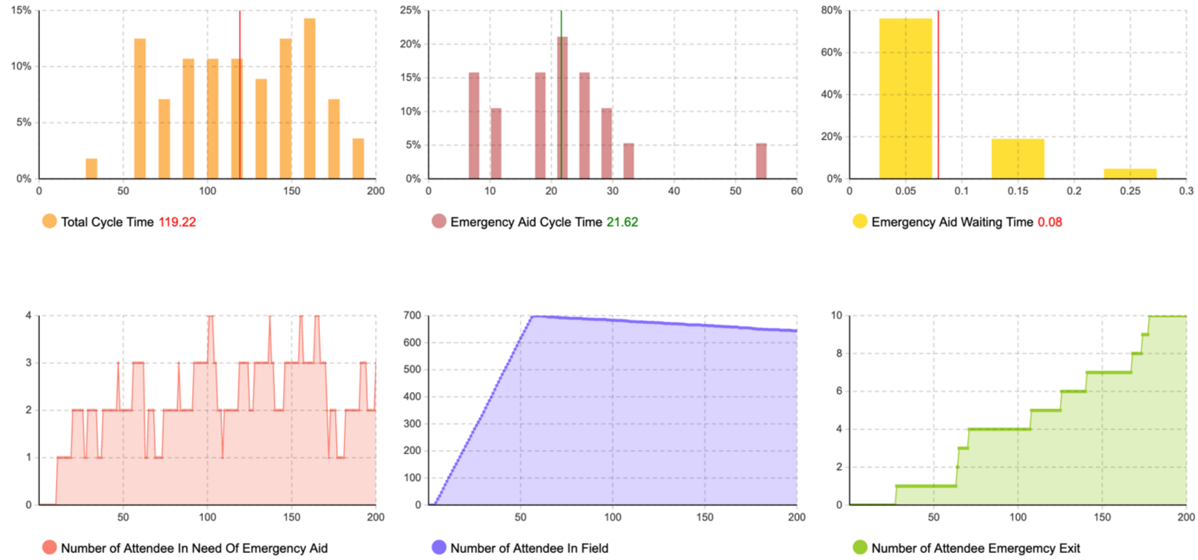


Figure 5. Performance metrics collected from the simulation

These metrics are defined to capture various stages of the attendee experience: total cycle time measures the duration attendees spend from entering the field to leaving, while emergency aid cycle time tracks the time patients spend from arriving at the emergency aid station to leaving. Emergency aid waiting time records the duration patients wait for medical treatment if immediate service is unavailable, a metric that is vital for identifying potential bottlenecks in the medical aid station. We also monitor the changing number of patients requiring emergency aid, the number of attendees in the field at any given time, and the number of serious patients needing hospitalization. By analyzing these metrics, the simulation offers insights on real-time assessment of medical needs and effective resource allocation during the event.

3.2. Simulation of High-Urgency Medical Emergencies and Cascading Effects

3.2.1. Simulation Proposition

In the previous sub-section, we modeled and visualized low-urgency medical emergencies. This sub-section focuses on a proposition of simulating of high-urgency medical emergencies during the event, specifically a stroke attack occurring in the middle of a dense crowd. This medical emergency simulation encompasses three key elements:

- **Trigger**: The scenario begins with a primary incident where an attendee collapses due to a stroke, which necessitates immediate medical intervention.
- **Crowd reaction**: In the immediate aftermath of the incident, nearby attendees notice the emergency and attempt to help the patient.
- **Cascading effects**: Potential secondary incidents may occur due to the emergency response. First, the sudden movement of people trying to clear a path for the medical team can cause congestion in other areas, which may increase the risk of tripping or falling. Second, the density of the crowd may impede the medical team's access to the patient, delaying critical care and potentially worsening the primary incident.

The emphasis of this situation is on initiating medical treatment within the first hour of the stroke's onset, commonly referred to as the "Golden Hour" (Saver et al., 2010). As shown in Figure 6, the total response time is broken down into five critical time segments:

- **Detection time**: The duration from the onset of the stroke to when the incident is first noticed by nearby attendees.
- **Notification time**: The time taken for the help request to be communicated to the medical team after the incident is detected.
- **Dispatch time**: The time taken for the medical team to be dispatched after receiving the notification.
- **Navigation time**: The time taken for the medical team to navigate through the crowd and reach the patient.
- **Treatment time**: The duration from when the medical team reaches the patient to when the patient starts receiving stroke treatment.

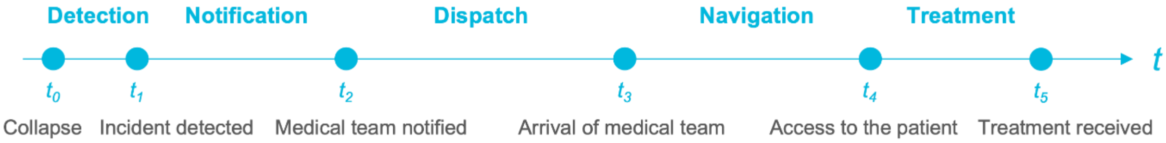


Figure 6. Critical time segments of the emergency response process

The approach involves developing and simulating what-if scenarios for emergency response. The simulation assesses various response strategies to help in determining the most effective ones. By optimizing these time segments, the objective is to reduce the overall response time and mitigate cascading effects during the medical emergency, ensuring that the stroke patient receives timely medical treatment.

3.2.2. What-if Scenarios Development

To evaluate the effectiveness of different emergency response strategies, we have developed a set of what-if scenarios as shown in Table 1. These scenarios use different communication methods for each critical time segment. Based on the scenarios, the simulation campaigns can be developed covering a wide range of combinations of response possibilities across each period. By implementing these simulations, we aim to compare different combinations and identify the optimal emergency response strategies in terms of minimizing response time and improving patient outcomes.

Table 1. What-if scenarios for critical time segments

Time Segment	Scenrio No.	Description
Detection	Scenario 1	Incident detected by nearby attendees.
	Scenario 2	Incident detected by drones.
	Scenario 3	Incident detected by surveillance cameras.
Notification	Scenario 1	Attendees call the medical team directly.
	Scenario 2	Attendees notify nearby security staff, who then alert the medical team.
	Scenario 3	Automated alerts from drones or surveillance systems.
Dispatch	Scenario 1	Medical team dispatched from a central location.
	Scenario 2	Medical team dispatched from pre-positioned strategic points.
Navigation	Scenario 1	Medical team navigates through crowds without designated pathways.
	Scenario 2	Medical team uses designated emergency pathways.
	Scenario 3	Real-time monitoring to find the quickest route.
Treatment	Scenario 1	Treating the patient at the hospital.
	Scenario 2	Treating the patient at the emergency vehicle through the deployment of communication technologies and telemedicine systems.

3.2.3. Data Requirements for Simulation Experiments

To create realistic models of the scenarios presented in Table 1, specific data and information are required for simulation experiments. Table 2 outlines the data and information needed for running each scenario within each time segment. By integrating this data into the simulation model, we can run experiments to evaluate the overall response time and identify critical factors that influence the efficiency of emergency responses.

In addition, the required data and information depend on the use of different communication technologies (such as drones, surveillance cameras, and telemedicine) specified in the scenarios. The use of advanced communication technologies can significantly impact the effectiveness of emergency response. By simulating scenarios that use these technologies and comparing them with scenarios that rely on traditional methods (such as direct calls, physical notifications), a comparative assessment of their impacts on response times and overall outcomes can be conducted.

Table 2. Data requirements for simulation experiments

Time Segment	Scenario No.	Data / Information required
Detection	Scenario 1	Reaction time of nearby attendees, crowd density, noise levels
	Scenario 2	Drone detection algorithms, detection time
	Scenario 3	Camera coverage, response time
Notification	Scenario 1	Call connection times, call duration, noise impact on communication
	Scenario 2	Staff availability, communication delay time
	Scenario 3	Automation algorithms, alert time
Dispatch	Scenario 1	Dispatch times, staff readiness
	Scenario 2	Dispatch times, strategic point locations
Navigation	Scenario 1	Crowd density data, navigation time estimates, obstacles
	Scenario 2	Pathway locations, crowd density around pathways, travel time estimates
	Scenario 3	Real-time crowd density data, dynamic route optimization algorithms
Treatment	Scenario 1	Transport time estimates, hospital readiness, patient condition data
	Scenario 2	Telemedicine equipment availability, communication system reliability, patient condition data

4. DISCUSSION

To further improve the realism of the scenario simulations and evaluate the practicality of different communication protocols, this study aims to incorporate data processing parameters derived from modern communication technologies. For instance, drones can significantly enhance incident detection across various scenarios. Programmed for rapid and autonomous deployment, they can reach incident sites much faster than ground vehicles, with professional units capable of speeds between 80 to 100 km/h. Equipped with high-resolution and thermal cameras, they provide real-time situational awareness. Information can be relayed to emergency teams using 5G systems with ultra-low latency between 1 and 10 milliseconds (Gupta et al., 2012). These capabilities support not only detection but also automated alerting; AI algorithms can identify incidents and broadcast notifications via 5G-compatible applications or SMS services, which maintain a 99.1% success rate with an average delivery time of 10.5 seconds (Orange, 2019).

To operationalize these technical capabilities within our framework, simulated incidents, such as a stroke patient collapsing, are introduced at known timestamps (t_0) to serve as event markers. The simulation logs the exact time of AI detection (t_1) and the subsequent alert generation (t_2). This allows for the precise calculation of detection intervals (t_1 - t_0) and alert intervals ($t_2 – t_1$). The integration of these technologies suggests a significant potential to compress the early stages of emergency response. By leveraging rapid deployment and low-latency transmission, drones can reduce detection gaps and provide event organizers with the situational awareness needed to identify the most efficient routes through dynamic crowd densities. Quantifying these impacts enables a comparative assessment of communication protocols, ensuring that response strategies are optimized to uphold the "Golden Hour" medical standard.

5. CONCLUSION

In this study, we introduced a framework integrating crowd simulation and cascading effect analysis to enhance emergency preparedness for mass gatherings. By assessing various response strategies, the framework provides a methodology for improving preparation protocols for emergency responders. The application of this framework was demonstrated through a music festival case study, modeling crowd dynamics and managing simulated medical emergencies. Furthermore, high-urgency scenarios, such as stroke attacks, were explored through what-if analyses to identify opportunities for minimizing response times.

Ultimately, this framework transitions emergency preparedness from reactive planning to a proactive, simulation-informed strategy. By accounting for cascading effects, event organizers can move beyond standard evacuation plans to identify latent bottlenecks created by the crowd's physical reaction to a medical crisis. The resulting decision-support dashboard allows responders to visualize critical trade-offs in resource allocation and pathway management. This approach facilitates the development of adaptive response protocols specifically designed to protect the "Golden Hour" window for patients in high-density environments.

Future research will focus on: first, incorporating real-world data from technology deployments to further refine simulation accuracy; second, expanding the model to cover diverse emergency scenarios and environments to increase its broad applicability. Continued collaboration with emergency responders, such as SDIS 62, remains vital for ensuring the framework's operational relevance and accuracy.

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