Agent-Based Modeling for the Simulation of Evacuation in Stadium GNP

Carla Reyes Hernández and Diego García-Gayou Ruiz

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1 Introduction

Entering and exiting a concert has become an unpleasant experience for most people, as they often encounter logistical disasters, overcrowding, and even theft of belongings. Efficient access management for large-scale events at the GNP Stadium in Mexico City is essential to ensure the safety of attendees and provide them with a quality experience. Last year, the Corona Capital music festival attracted 80,000 people in a single day, highlighting the enormous logistical and security challenge involved in coordinating the entry and exit of such a large crowd.

Incidents such as the 2010 Love Parade, where a lack of proper planning resulted in the deaths of 21 people due to overcrowding at the event's only entrance, underscore the risks associated with organizing large-scale events. These examples highlight the importance of logistics and careful planning to minimize risks and ensure the safety of all attendees. Therefore, we are seeking to establish protocols that optimize the exit of attendees to large-scale events at GNP Stadium in case of an emergency, ensuring a smooth and safe experience. We will conduct an exhaustive study to identify the most effective strategies for orderly exit GNP Stadium, defining door openings and which barriers or obstacles are necessary to avoid overcrowding. In this way, attendees' safety will ways be be first.

To achieve this, we model the Stadium GNP using agent-based modeling (abm) and principles of crowd dynamics. Agent-based modeling allows us to simulate the actions and interactions of individual "agents" in the stadium—to observe how collective behavior emerges in response to various evacuation scenarios. On the other hand we used the social force model as our crowd dynamics theory, to model how pedestrians would behave and interact following certain motivations and repulsion.

This model aims to identify potential bottlenecks, evaluate the effectiveness of different evacuation routes, and ultimately support risk mitigation strategies.

2 Implementation

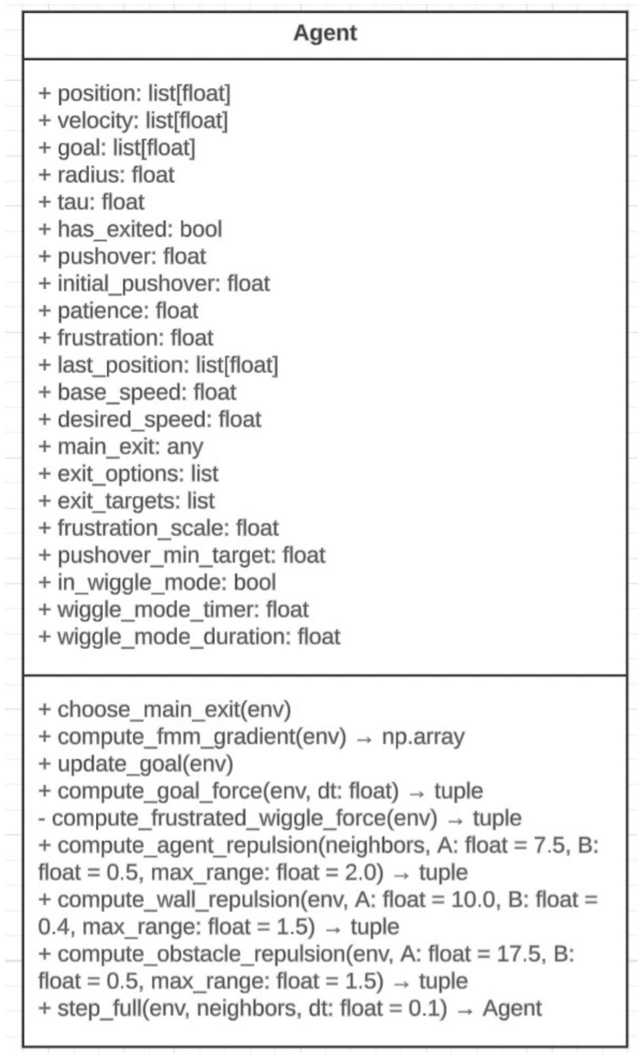
The simulation of the evacuation at GNP Stadium was developed using an agent-based modeling approach grounded in the social force model. The codebase was modularly designed using python. The code can be found in the following GitHub Repository

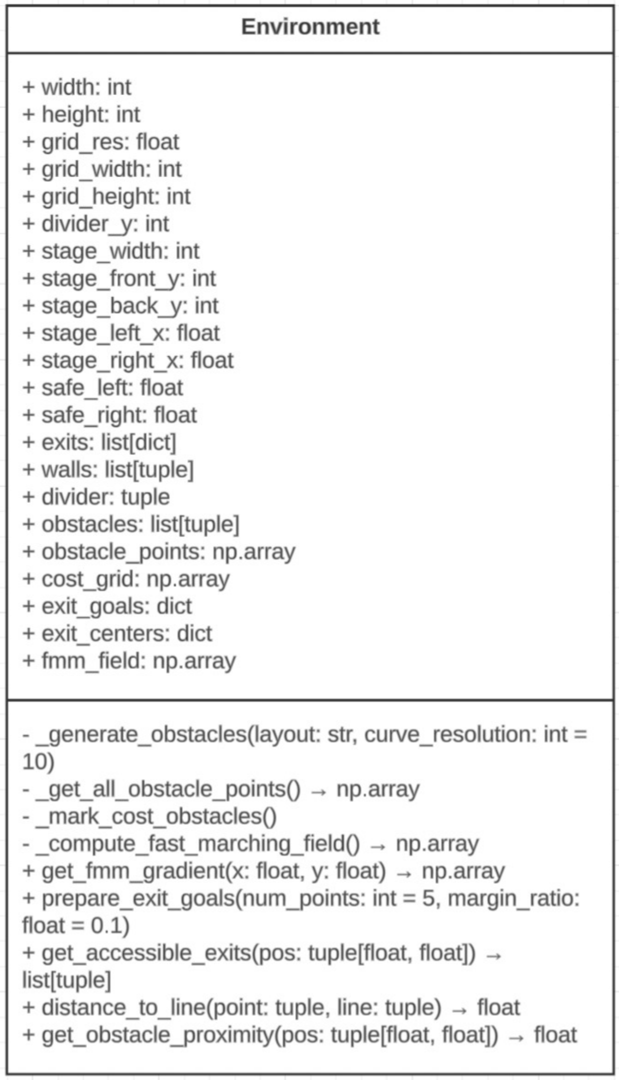
2.1 System Architecture

The project is organized into several key modules:

- `simulation.py`: Orchestrates the simulation loop and agent updates.
- `agents.py`: Defines the behavior of individual agents, including their social forces.
- `environment.py`: Models the physical layout of the stadium, exits, walls, and obstacles.
- `agent_distribution.py`: Handles the initial spatial distribution of agents using rejection sampling.
- `precompute_simulation.py`: Executes and stores full simulation outputs, such as positions and metrics.
- `density_analysis.py`: Computes crowd density statistics for analysis.
- `visualize_simulation.py`: Renders animations and plots showing agent movement, density, and risk metrics.

2.2 UML of Agent and Environment





2.3 Agents

Agents in our simulation represent individual pedestrians, each governed by a variant of the Social Force Model. Each agent is different because it incorporates personalized behavioral traits to simulate various reactions in a crowd scenario. At initialization, each agent is assigned a random position and a unique radius, representing physical size, as well as a "pushover" coefficient. This coefficient represents the agent's sensitivity to social repulsion forces and also influence attributes such as desired speed and patience.

The agents' behaviors are not scripted in a top-down fashion but rather emerge from local interactions with other agents and the environment. Their dynamics arise from forces such as goal attraction (toward exits), agent-agent repulsion (to avoid collisions), and wall avoidance. This represents the concept of weak emergence, where complex group dynamics—such as bottlenecks or jams emergence from individual rules.

Furthermore, agents can be extended into categories of increasing complexity as presented in the ABM lecture: they currently operate as interested agents, reacting to environmental conditions with internal motivations.

The motion of each agent is governed by the sum of five force components:

- A **goal force** that propels the agent toward its current target exit, based on the shortest distance and zone compatibility.
- A **repulsive force** from neighboring agents, scaled by their proximity and the agent's pushover trait.
- A **wall repulsion force** to avoid collisions with stadium boundaries.
- A **obstacle repulsion** to avoid collisions with static obstacles.
- A **wiggle force** a force that overrides the goal direction when agents are frustated and have not been moving, this incentives exploration.

Agents dynamically select their primary exit based on reachability and proximity to designated exit zones. They continuously update their goal points to the closest valid target within that exit zone.

A frustration mechanism is integrated to simulate behavioral shifts under congestion. When an agent experiences limited movement over time, their internal frustration counter increases. If this exceeds their patience threshold, they exhibit temporary surges of acceleration to reattempt progress toward their goal.

2.4 Environment

The environment in our simulation models the layout of the GNP Stadium as a two-dimensional continuous space of $130\,m \times 100\,m$. This spatial has features such as a central divider, enclosing walls, a stage area at the top, and three primary exit regions located at the bottom, left, and right edges of the space. The environment is further segmented horizontally to distinguish between front and back audience sections.

A key computational component of the environment is the use of the Fast Marching Method (FMM) to precompute a potential field that represents the shortest arrival time to the nearest goal point (exit) from any position in the environment. This potential field acts as a navigation map that allows agents to follow optimal paths toward exits, avoiding obstacles and dead ends.

Each exit area is associated with multiple goal points, and the FMM is run for each exit to generate a set of direction fields. These are later interpolated to guide agent movement in real time, providing decentralized and reactive navigation. Zones around goal points define successful evacuations—agents that reach these zones are removed from the simulation.

2.5 Simulation

The simulation operates as a discrete-time, agent-based system in which the state of each agent is updated at every frame based on local interactions with the environment and other agents. At initialization, agents are placed in the environment using a spatially biased distribution to reflect real-world crowd densities. Each agent is assigned a preferred exit based on reachability and proximity, informed by the Fast Marching Method (FMM) pathfinding fields.

Each simulation step proceeds through the following phases:

1. **Filtering Active Agents:** Only agents that have not yet reached an exit are included in the update cycle.

2. **Neighbor Detection:** A KDTree spatial index is used to identify nearby agents within a 3-meter radius. These neighbors contribute to repulsive social forces in the Social Force Model.

3. **Parallelized Agent Updates:** Each active agent computes a new candidate state in parallel, including position, velocity, and internal metrics such as frustration. This step integrates three key influences: goal attraction via the FMM-derived potential field, agent-agent repulsion, and wall avoidance.

4. **State Synchronization:** After parallel computation, the original agent objects are updated with the new positions and velocities to reflect a consistent global state.

5. **Exit Detection:** Agents are flagged as "exited" when they cross any defined exit line within a 0.5-meter spatial threshold. This ensures a physically accurate and forgiving representation of successful egress.

The simulation tracks the elapsed frame count and halts automatically when all agents have exited or a predefined maximum number of frames is reached.

To assess the evolving risk of overcrowding, a *crush index* is computed at each frame. This index is defined as the product of the maximum local density (computed over 1m $\times$ 1m spatial bins) and the average "pushover" parameter of all remaining agents. It serves as a proxy for identifying high-risk congestion zones, aligning with ABM's strength in uncovering emergent spatial-temporal patterns.

2.6 Agent Distribution

To simulate realistic crowd conditions, agents are not placed uniformly across the environment. Instead, we apply a probabilistic distribution strategy that reflects higher crowd densities near key areas, such as the stage and central divider.

The environment is divided into two main zones: a **bottom section** and a **top section**, separated by a horizontal divider. Agent positions are sampled using a *rejection sampling* method, in which random candidate positions are accepted based on a sigmoid-shaped density function that increases crowd concentration toward a central vertical band (e.g., closer to the stage or divider).

- In the **bottom section**, agent density is biased toward the divider mimicking crowd accumulation near popular exits or barriers.
- In the **top section**, sampling also avoids the designated stage area using a masking function to prevent agents from spawning in non navigable regions.

This approach produces a more heterogeneous and realistic spatial layout, with clusters of agents in high-interest zones and sparser populations in peripheral areas.

2.7 Visualization

To support interpretation of the simulation results, a custom visualization tool was developed. This tool processes saved simulation data and generates multiple informative plots that help characterize crowd dynamics, evacuation efficiency, and potential safety risks.

The following visual outputs are generated:

- **Evacuation Progress:** A line plot showing the number of remaining agents over time, providing insight into overall evacuation speed and efficiency.
- **Exit Rate:** A time series of the number of agents exiting per second, highlighting burst patterns or stagnation in flow.
- **Crowd Density Metrics:** Plots of maximum, mean, and 95th-percentile crowd density across time, derived from 1m $\times$ 1m spatial binning of agent positions.
- **Crush Index:** A graph of the crush index over time, computed as the product of local crowd density and the average assertiveness (pushover) of remaining agents.
- **Animated Visualization:** A real-time animation of agent movement throughout the stadium, with colors indicating each agent's pushover trait. Walls and exits are rendered to provide spatial context.

These visualizations are essential for diagnosing congestion, identifying high-risk zones, and validating the effects of configuration changes. Color gradients in the animation allow quick assessment of behavioral traits in crowd flow, while statistical plots quantify critical metrics for safety evaluation.

2.8 Assumptions and Limitations

The simulation assumes rational agent behavior under the social force model and does not account for panic, communication, or visibility constraints. Wall and stage geometry are simplified representations of the real stadium layout.

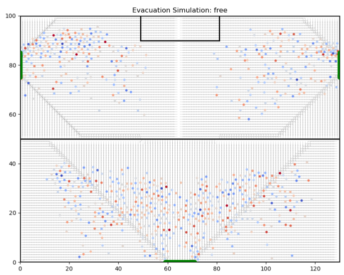
3 Experiments

To evaluate the dynamics of crowd movement and emergent behaviors under different architectural constraints, we designed and simulated four experimental scenarios:

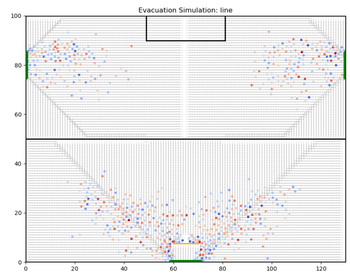
- **No Obstacles** — An open stadium layout with no additional structures obstructing movement.
- **Horizontal Barrier** — A wall placed horizontally near the exit at the bottom of the environment.
- **V-Shape** — A V-shaped obstacle placed in front of the central exit, forcing agents to spread before converging.
- **Parabola** — A curved parabolic barrier before the bottom exit.
- **Funnel** — A funnel-shaped configuration that narrows paths toward the exit.

Each scenario was initialized with an identical number of agents (1000) and uniform behavioral parameter distributions to ensure comparability. The primary goal is to assess how environmental constraints influence evacuation efficiency, agent congestion, and emergent risk patterns.

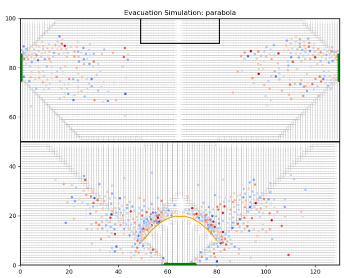
3.0.1 Simulation Screenshots



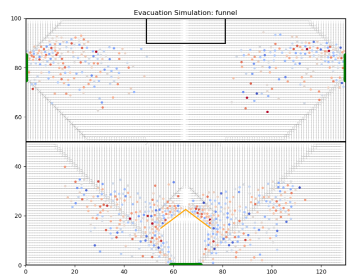
(a) No Obstacles



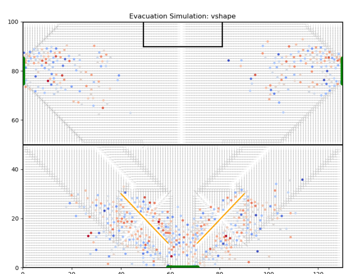
(b) Horizontal Barrier



(c) Parabola



(d) Funnel



(e) V Shape

Figure 1: Simulation screenshots for different obstacle configurations.

3.1 Metrics

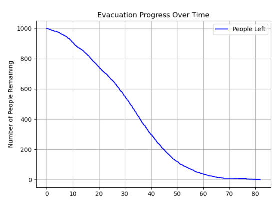
We tracked several quantitative metrics across all scenarios:

- **Agents remaining across time** — How many agents were left at each time
- **Exit throughput over time** — At each 0.1 seconds, measures how many agents are exiting.
- **Crowd density statistics over time** — How dense is the scenario, it plots the maximum density, the 95th percentile density and the average density, in a 1mx1m.
- **Crush risk over time** — It is the product of the maximum local density (measured in 1m × 1m bins) and the average 'pushover' trait of all remaining agents.

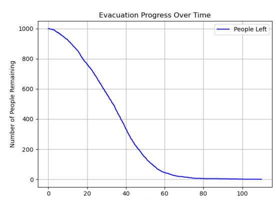
3.2 Visual Comparison

For each metric, we present a snapshot of graphs for each scenario.

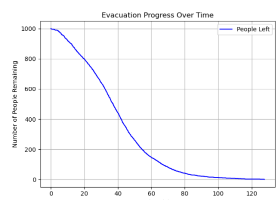
3.2.1 Evacuation Progress Over Time



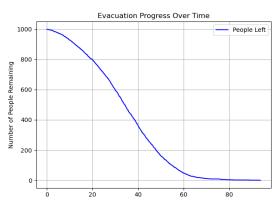
(a) No Obstacles



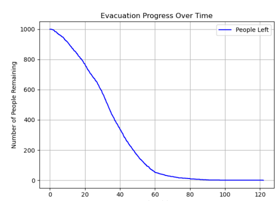
(b) Horizontal Barrier



(c) Parabola

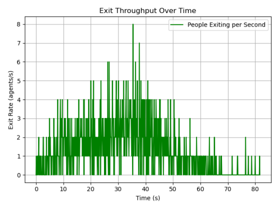


(d) Funnel

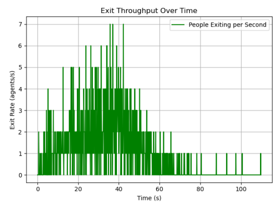


(e) V Shape

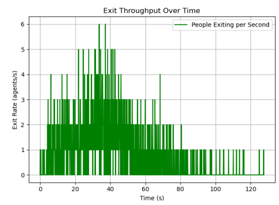
3.2.2 Exit Throughput Over Time



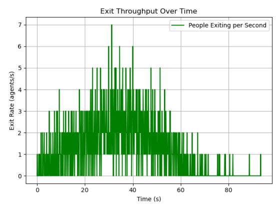
(a) No Obstacles



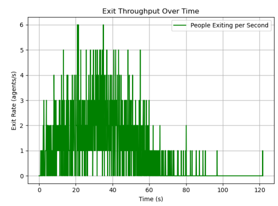
(b) Horizontal Barrier



(c) Parabola

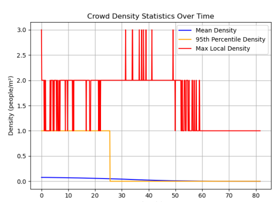


(d) Funnel

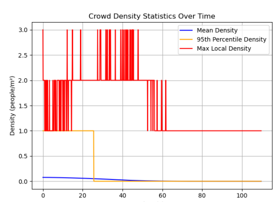


(e) V Shape

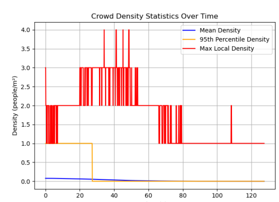
3.2.3 Crowd Density Statistics Over Time



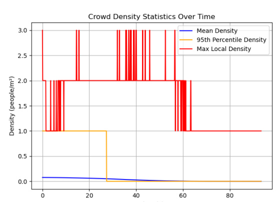
(a) No Obstacles



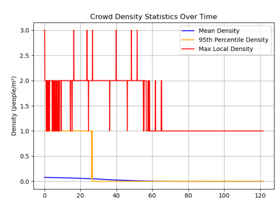
(b) Horizontal Barrier



(c) Parabola

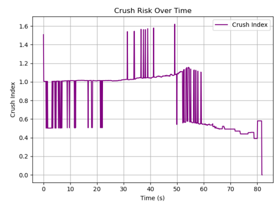


(d) Funnel



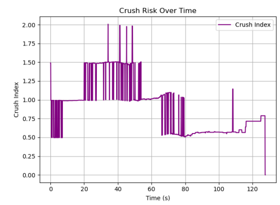
(e) V Shape

3.2.4 Crush Risk Over Time

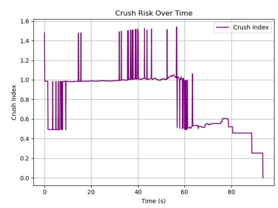


(a) No Obstacles

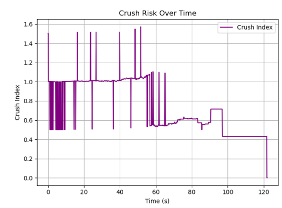
(b) Horizontal Barrier



(c) Parabola



(d) Funnel



(e) V Shape

3.3 Discussion

After running the experiments with the five different layouts and analyzing the metrics, these are the results we found. V-Shape and Horizontal Barrier have a steeper slope, which means that they maximize the amount of people who leave the stadium fast, but They also have longer tails, so people who are not as fast will still remain in the stadium. No obstacles and funnel allows an even distribution of the amount of people leaving. Finally parabola is the worst in terms of a long and dense tail, which means people get often more stuck.

Exit throughput (amount of people leaving the stadium at a given time) is a way of verifying the conclusions found on the remaining agents vs time curves. Horizontal and V Shape are tighter, and allow the people to leave the stadium faster and reach the maximum of people leaving earlier. No obstacles and funnel have a wider spread, and parabola has the longer tail.

In crowd density statistics over time the most important case is the maximum local density, because the worst cases are that ones were too many people at the same time lead to accidents and tragedies. Here we found that V-Shape minimizes the spikes of maximum local density, followed by no obstacles and funnel. Parabola is the most dangerous one, it even reaches a maximum local density of 4, something that the other obstacles do not do. These could lead to accidents and people getting crushed.

Finally, crush risk is tightly tight to maximum local density since it is the product of maximum local density and the average pushover on that square of the agents. Again, the obstacle that is able to minimize the crush risk is V-Shape.

In conclusion, no obstacles and Funnel are the best models time wise, but V-Shape allows a safely evacuation of the stadium and allows the people to exit the stadium fast. All these results are subject to the location of the obstacles, different placements, lengths and widths can lead to more or less effective evacuations. The primary purpose of our simulation environment is for policy makers to test their ideas safely.