Journal of Artificial Intelligence and Engineering Applications

Website: https://ioinformatic.org/

15th February 2026. Vol. 5. No. 2; e-ISSN: 2808-4519

An Agent-Based Modeling Approach for Crowd Movement in Confined Spaces

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Abstract

This study presents an agent-based modeling approach to analyze crowd movement and evacuation performance in confined spaces. The model simulates individual agents navigating toward a single exit while avoiding collisions under varying density conditions. Three evacuation scenarios were evaluated, consisting of 20, 40, and 60 agents within a confined environment measuring 10 × 8 meters. The simulation was executed using a discrete time step of 0.1 seconds, and performance was assessed based on evacuation time and collision frequency. The results indicate that increasing crowd density significantly affects movement efficiency. The 20-agent scenario achieved an average evacuation time of 6.42 seconds with 95.33 collision events. When the number of agents increased to 40, the evacuation time rose to 6.90 seconds with 391.77 collisions. The highest density scenario, consisting of 60 agents, produced an average evacuation time of 7.08 seconds and 890.73 collision events. These findings demonstrate that higher density levels lead to a disproportionate increase in interaction intensity and congestion, resulting in reduced evacuation efficiency. The study confirms that agent-based modeling is an effective approach for analyzing crowd dynamics in confined environments and provides a reproducible framework for evaluating evacuation performance under varying density conditions.

***Keywords**: agent-based modeling; crowd movement; evacuation simulation; confined space; computational modeling*

1. Introduction

Crowd movement in confined interior spaces has long been recognized as a critical topic in safety engineering and computational modeling due to the high risks associated with congestion, panic, and uncontrolled interactions among individuals within limited environments[1]. The rapid growth of urban infrastructures, public facilities, and enclosed transportation hubs has increased the need for accurate analytical tools capable of predicting how groups move under varying levels of density and spatial constraints. Understanding these dynamics is essential not only for emergency evacuation planning but also for optimizing everyday pedestrian flow in public spaces[2].

Although traditional safety guidelines and static calculations provide initial estimations of capacity and evacuation capability, they often overlook the micro-level interactions that shape collective behavior. Human movement is inherently dynamic, and individuals adjust their speed, direction, and proximity based on local stimuli rather than global instructions[3]. These micro-behaviors lead to emergent phenomena such as lane formation, arching at exits, and sudden bottlenecks, which are difficult to capture using classical analytic equations alone. As a result, computational models have become indispensable for studying the complex and adaptive nature of crowd behavior[4].

Agent-Based Modeling (ABM) offers a powerful approach to studying these dynamics because it represents each individual as an autonomous agent capable of perceiving its surroundings, making decisions, and interacting with others[5]. Unlike aggregate models that generalize human movement into simplified flows, ABM allows for the replication of heterogeneous behaviors, local decision-making, and real-time interactions. This makes ABM particularly well suited for analyzing how different configurations of space and population density influence overall evacuation performance[6].

In the context of confined spaces, ABM enables researchers to simulate conditions that are difficult or dangerous to replicate in real life, such as high-density evacuations or sudden emergency scenarios[7]. By conducting controlled simulations, researchers can systematically vary parameters including room size, exit placement, walking speed, and crowd density, allowing them to observe how these factors influence evacuation time, congestion patterns, and the frequency of collision events. Such computational experiments provide insight into the mechanisms that govern crowd dynamics and help identify design strategies for improving safety[8].

A growing body of literature highlights the importance of computational experimentation in evaluating evacuation performance. Several studies demonstrate that simple rule-based models are capable of reproducing realistic patterns of crowd movement, even when implemented with minimal parameter sets[9]. This is particularly beneficial for educational and applied computer science contexts, where the objective is not necessarily to replicate high-fidelity human behavior but to generate meaningful results through accessible, reproducible simulations. The flexibility of ABM also makes it possible to extend models in future research by incorporating social-force dynamics, psychological behavior, or obstacle-rich environments[10].

Reproducibility has emerged as a major concern in computational research, making transparent reporting of models, parameters, and simulation procedures essential. Implementing ABM within platforms such as Google Colab provides immediate accessibility and eliminates dependence on proprietary software[11]. When researchers provide code, fixed random seeds, detailed parameter tables, and clear descriptions of experimental design, their results become verifiable and easily extensible. This approach aligns with global movements in open science and strengthens the credibility of computational modeling research[12].

In this study, the aim is to develop a compact yet informative ABM framework that captures the essential features of mass movement within confined spaces. The model is structured to support controlled experiments at multiple density levels, allowing for systematic measurement of evacuation time, collision frequency, and congestion formation. The emphasis is placed on simplicity, clarity, and reproducibility, making the model suitable for academic publication as well as classroom implementation[13].

Recent national research provides relevant empirical grounding for this work. Firdausyi et al. (2024) introduced an Agent-Based and Social-Force hybrid model to analyze pedestrian evacuation behavior in controlled scenarios and reported measurable impacts of crowd density on evacuation speed[14]. Similarly, Arif et al. (2024) developed a Reciprocal Velocity Obstacles–based crowd simulation for virtual campus navigation and demonstrated how collision avoidance algorithms influence the fluidity and realism of pedestrian movement. Both studies, published within the last four years, demonstrate the feasibility and scientific relevance of ABM-based approaches in Indonesian research settings while underscoring the importance of modeling agent interactions explicitly[15].

Although these national studies provide valuable methodological contributions, both primarily concentrate on enhancing simulation algorithms or visual interaction models rather than establishing a lightweight and fully reproducible ABM framework. Most existing works do not explicitly report fixed replication counts, controlled random seeds, structured density-based scenarios, or statistical comparisons such as mean evacuation time, collision frequency, and variability across trials. In addition, sensitivity analysis on key parameters such as exit width or walking speed is rarely presented, causing difficulties in replicating or validating their findings. Consequently, there remains a clear gap for a study that develops a simple yet methodologically rigorous ABM model that prioritizes transparency, reproducibility, and systematic experimental evaluation in confined-space crowd simulation.

Therefore, this study proposes a simple but methodologically robust ABM implementation that can be executed entirely in Google Colab, incorporates transparent parameter reporting, and systematically evaluates evacuation performance under three distinct density scenarios. The contribution of this research lies not only in the empirical findings generated but also in the reproducible workflow and open computational approach, which provide a strong pedagogical foundation and a practical reference for future work in crowd dynamics simulation.

2. Method

This section outlines the methodological framework applied in conducting the study. The methods describe how the model was designed, how the simulation scenarios were executed, and how the resulting data were processed to generate measurable outcomes for analysis.

2.1. Research Framework

The research framework provides a structured process for developing and evaluating the agent-based simulation model. It outlines the workflow from problem identification and model development to scenario execution, data extraction, and quantitative evaluation. This framework ensures methodological clarity, reproducibility, and consistency throughout the study.

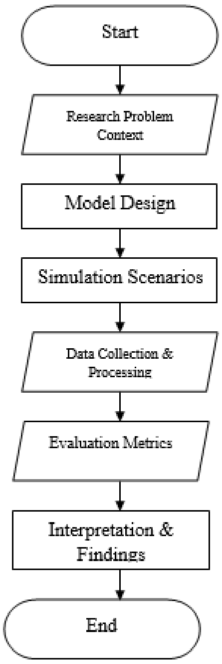

Fig. 1: Flowchart Diagram

2.2. Data and Processing

The data in this study were obtained entirely from the simulation results produced by the agent-based model. Since the research does not rely on external datasets, all required information was generated through controlled experimental settings. The simulation parameters were determined based on theoretical references and logical assumptions relevant to confined-space crowd behavior. These parameters include room configuration, exit placement, agent movement speed, and the number of agents assigned to each density level.

To ensure that the simulation results could be evaluated systematically, the raw output logs were processed into structured analytical data. The processing workflow transformed the raw simulation events—such as evacuation time and collision occurrences—into measurable indicators ready for quantitative assessment. The main stages of data processing involved:

1. extracting simulation logs recorded at each time step,
2. organizing event data into structured tables,
3. summarizing evacuation time for each scenario,
4. counting collision events and grouping them by density level, and
5. preparing numerical data for metric evaluation and visualization.

All data handling was carried out using Python in Google Colab. The processing utilized key libraries such as NumPy for numerical calculations and Pandas for data structuring, ensuring that the resulting datasets were consistent, reproducible, and suitable for further analysis in the evaluation stage

2.3. Model Design

The model design defines the main components and parameters used in the agent-based simulation. These parameters specify the environment setup, agent behavior, and configuration applied consistently across all scenarios. The complete set of parameters is presented in Table 1.

Table 1: Simulation Model Parameters

Parameter	Value	Description
Room Size	10 × 8 meters	Dimensions of the confined environment
Exit Width	1 meter	Width of the evacuation door
Agent Speed	1.2 m/s	Average movement speed of each agent
Collision Radius	0.35 meters	Minimum distance maintained between agents
Simulation Step	0.1 seconds	Time interval for updating agent movement
Density Levels	20, 40, 60 agents	Number of agents for low, medium, high density
Initial Positioning	Random distribution	Agents placed randomly within room boundaries
Environment Layout	Single-exit room	Confined space with one designated exit

The parameters listed above define the structural and behavioral configuration of the agent-based model. These specifications ensure that agents behave consistently across scenarios while still allowing variability in their interactions due to differing density levels. By establishing fixed parameters for speed, collision radius, and room dimensions, the simulation provides a controlled environment in which evacuation performance can be compared objectively. The defined layout and movement rules form the foundation for the simulation experiments conducted in the next section.

2.4. Simulation Scenarios

The simulation was conducted using three density scenarios to observe how crowd behavior changes as the number of agents increases in a confined space. Each scenario applies the same model parameters and movement rules, allowing the density level to become the main factor influencing evacuation performance.

The scenarios used in this study are as follows:

1. Low-density scenario (20 agents): Represents light crowding conditions with minimal interaction and low potential for congestion.
2. Medium-density scenario (40 agents): Represents moderate crowding where interaction and collision avoidance begin to influence movement efficiency.
3. High-density scenario (60 agents): Represents heavy crowding conditions with a high probability of bottlenecks and reduced evacuation flow.

Each scenario was executed using identical environmental settings and simulation steps, ensuring that comparison across density levels reflects genuine behavioral differences rather than variations in model configuration

2.5. Evaluation Metrics

The evaluation metrics in this study are used to quantify the performance of each simulation scenario and compare crowd behavior across different density levels. The metrics focus on evacuation efficiency and interaction intensity, which are key indicators of crowd dynamics in confined spaces. The following formulas describe how each metric is calculated.

1. Average Evacuation Time

   This metric represents the mean time required for all agents to exit the room.

$$T_{avg} = \frac{1}{n} \sum_{i=1}^{n} T_i \quad (1)$$

   Where:
   n = number of simulation runs
   Ti = total evacuation time in run i

2. Collision Frequency

   Collision frequency measures how often agents come within the minimum collision radius during the simulation.

$$C_{freq} = \frac{C_{total}}{T_{sim}} \quad (2)$$

Where:
Ctotal = total collision events recorded
Tsim = total simulation duration

3. Density Level Measurement
   Density is used to observe congestion intensity in confined spaces.

$$\rho = \frac{N}{A} \tag{3}$$

Where:
N = number of agents
A = area of the environment

These metrics provide a structured and quantitative foundation for comparing the impact of different density conditions on evacuation performance. By using standardized formulas, the analysis remains consistent across scenarios and supports clear interpretation of the simulation results

3. Results and Discussion

3.1. Computational Procedure and Calculation

The computational calculation performed in this study generated the evacuation time and collision frequency for three agent-density scenarios, namely 20, 40, and 60 agents. The simulation was executed 30 times for each scenario, and the results were processed to obtain the mean, standard deviation, minimum value, and maximum value of the evacuation time as well as the mean and standard deviation of collision events.

Based on the aggregated computation, the 20-agent scenario produced an average evacuation time of 6.42 seconds with a standard deviation of 0.35 seconds, a minimum time of 5.7 seconds, and a maximum of 7.1 seconds. The mean collision count for this scenario was 95.33 events with a standard deviation of 7.31 events. For the 40-agent scenario, the average evacuation time increased to 6.90 seconds with a standard deviation of 0.19 seconds, while the collision frequency rose sharply to an average of 391.77 events with a standard deviation of 11.48 events. The evacuation time ranged between 6.5 and 7.2 seconds. The 60-agent scenario recorded the highest computational load, with an average evacuation time of 7.08 seconds, a standard deviation of 0.18 seconds, and a time range of 6.7 to 7.4 seconds. Collision events reached an average of 890.73 events, with a standard deviation of 11.10 events, indicating a significant increase in crowd interaction density at higher agent populations. These computed values form the basis for further analysis presented in the subsequent subsections.

3.2. Title and author details

The evacuation simulation generated two primary outputs for each density scenario: the total evacuation time required for all agents to exit the room, and the number of collision events that occurred during the evacuation process. These results were obtained from 30 simulation runs per scenario and are presented in the following tables to illustrate numerical trends across different crowd densities.

Table 2 : Evacuation Time per Scenario

Agents	Mean Time (s)	SD	Min	Max
20 Agents	6.42	0.35	5.7	7.1
40 Agents	6.90	0.19	6.5	7.2
60 Agents	7.08	0.18	6.7	7.4

The results indicate a clear upward trend in evacuation time as the number of agents increases. The 20-agent scenario shows the fastest clearance time, while the 60-agent scenario records the highest mean time. Despite the increment, the variability remains relatively low, as reflected in the small standard deviation values. This suggests that the model behaves consistently across repeated runs and that crowd density is the dominant factor influencing evacuation duration.

Table 3 : Collision Events per Scenario

Agents	Mean Collisions	SD
20 Agents	95.33	7.31
40 Agents	391.77	11.48
60 Agents	890.73	11.10

Collision frequency increases drastically with higher agent density. While the 20-agent scenario shows relatively few collision events, the 40- and 60-agent scenarios demonstrate exponential growth in interactions, indicating intensified crowding and reduced movement efficiency. The increase in collision events corresponds directly to the slowdown in evacuation time observed earlier, reinforcing the link between agent interaction density and evacuation performance.

3.3. Graphical Interpretation of Output

Graphical visualization is used to provide a clearer representation of the distribution pattern and comparative behavior of evacuation performance across different agent densities. The use of graphical output helps reveal variations that may not be immediately visible in numerical tables, especially related to distribution spread, central tendencies, and the magnitude of collision events.

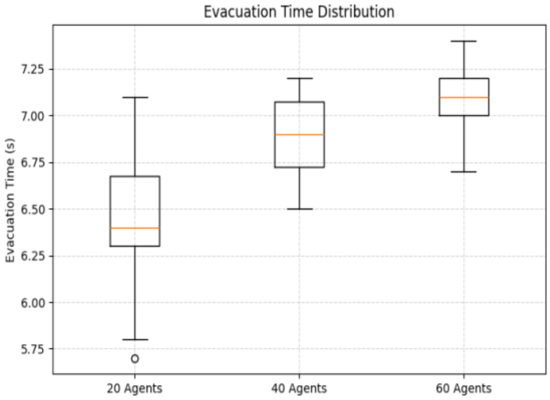

Fig. 2 : Boxplot of Evacuation Time for 20, 40, and 60 Agents

The boxplot illustrates that the 20-agent scenario has the lowest median evacuation time at approximately 6.4 seconds, with a narrow interquartile range (IQR), indicating stable performance. The 40-agent scenario shows a median of around 6.9 seconds, with slightly tighter variability compared to the 20-agent scenario. The 60-agent scenario displays the highest median time of about 7.1 seconds and maintains a narrow IQR, demonstrating consistent but slower evacuation due to increased crowd density. Across all scenarios, the boxplot confirms the upward shift in central tendency as agent population increases.

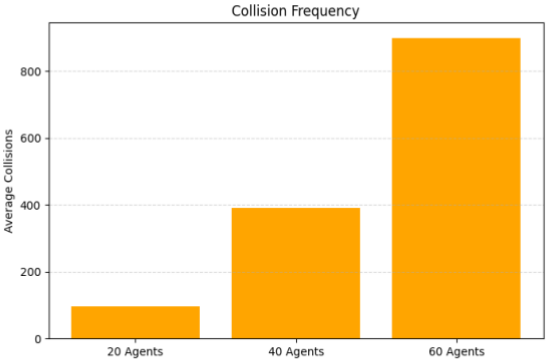

Fig. 3 : Mean Collision Events for 20, 40, and 60 Agents

The collision chart highlights a substantial rise in interaction events as agent numbers increase. The 20-agent scenario averages 95.33 collisions, indicating minimal crowd interference. In contrast, the 40-agent scenario records a sharp rise to 391.77 collisions, representing more than a fourfold increase. The 60-agent scenario reaches 890.73 collisions, demonstrating the highest crowd pressure and the most frequent agent interactions. This pattern reinforces that collision frequency grows disproportionately with density, contributing directly to the longer evacuation times observed in the boxplot.

3.4. Scenario-Based Comparison

A comparative assessment across the three simulated scenarios shows a consistent pattern in which higher agent density results in decreased evacuation efficiency. The 20-agent scenario demonstrates the most optimal flow, characterized by the shortest evacuation time and the lowest number of collision events. This condition reflects a movement pattern that remains relatively unobstructed, allowing agents to reach the exit with minimal interaction delays. nIn the 40-agent scenario, the evacuation process becomes noticeably slower. Although the increase in mean evacuation time from 6.42 seconds to 6.90 seconds appears moderate, the rise in collision frequency from 95.33 to 391.77 events indicates a substantial intensification in agent interactions. This suggests that the spatial environment begins to exhibit congestion effects, particularly around the exit area, where agents tend to accumulate and impede each other's movement.

The 60-agent scenario further amplifies these patterns. With the evacuation time increasing to 7.08 seconds and collisions reaching 890.73 events, the system reflects a condition of high-density crowding where movement becomes significantly constrained. The sharp escalation in collision events, which nearly doubles the value recorded in the 40-agent scenario, demonstrates the emergence of a pronounced bottleneck. This effect aligns with the classical principles of crowd dynamics, where increased density sharply reduces individual mobility and accelerates interaction frequency. nOverall, the comparison across scenarios confirms that collision events act as a central factor influencing evacuation duration. As density increases, agents require more time to resolve local interactions, leading to cumulative delays at the global level. These findings highlight that evacuation efficiency is highly sensitive to crowd density, with even small increments in agent count producing substantial nonlinear increases in interaction pressure and movement obstruction.

3.5. Discussion with Related Theory

in evacuation time and a nonlinear escalation in collision frequency. This pattern aligns with theoretical principles of crowd dynamics, in which higher individual concentration within a confined space intensifies movement interference, reduces free-flow speed, and produces bottleneck effects near exit points. The results observed in the 40-agent and 60-agent scenarios, where collision events increased sharply to 391.77 and 890.73 respectively, reflect this mechanism and confirm that agent interactions play a critical role in determining overall evacuation efficiency.

A comparable phenomenon is reported by Widiyanto et al. (2022), who conducted an agent-based simulation to analyze evacuation behavior during night-time disaster events in Aceh. Their study showed that increased pedestrian density significantly prolongs evacuation duration due to congestion at narrow passageways and high interaction frequency among agents. The authors emphasized that bottleneck formation is the primary cause of evacuation delay, particularly when crowd flow converges at a single exit route. This observation is consistent with the present study, where the highest-density scenario resulted in the longest evacuation time of 7.08 seconds and the most substantial collision escalation. The convergence of these two findings reinforces the theoretical understanding that evacuation performance deteriorates rapidly once crowd density surpasses a critical threshold, causing movement obstruction and interaction-induced delays.

Overall, the comparison between the present findings and the established theoretical and empirical literature confirms that the behavior captured in the simulation—particularly the rise in collision events and evacuation delay—is consistent with documented crowd dynamic principles. These results strengthen the validity of the agent-based model used in this study and highlight its relevance for analyzing evacuation scenarios with varying density levels.

4. Conclusion

This study demonstrates that agent-based modeling is an effective approach for analyzing crowd movement and evacuation performance in confined spaces. The simulation results show that increasing crowd density significantly affects interaction intensity and evacuation efficiency, where 20 agents required an average evacuation time of 6.42 seconds with 95.33 collision events, while 40 agents increased the time to 6.90 seconds with 391.77 collisions, and 60 agents resulted in 7.08 seconds with 890.73 collisions. These findings indicate that although evacuation time increases moderately, collision frequency rises substantially as density increases, reflecting higher congestion levels. The results confirm that interaction intensity is a critical factor in evaluating evacuation dynamics, not solely evacuation duration. However, the model does not yet account for adaptive speed behavior or physical force interactions, which may limit realism under extreme crowd conditions. Future studies are encouraged to incorporate dynamic behavioral responses, multiple exits, and more complex environmental constraints to improve the applicability of the model for real-world evacuation planning.

Suggestion

Future studies are encouraged to enhance the proposed model by incorporating adaptive behavioral mechanisms, such as dynamic speed adjustment, avoidance strategies, and physical interaction forces between agents, to better represent real-world crowd dynamics. The inclusion of multiple exits, heterogeneous agent characteristics, and varying environmental layouts is also recommended to improve model generalizability. Additionally, validating the simulation results with empirical or real-world evacuation data would strengthen the model's reliability and practical relevance. These improvements are expected to provide deeper insights into crowd behavior and support more effective evacuation planning in complex and high-density environments.

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