Hybrid PSO-SFM Algorithm for Intelligent Multi-Floor Emergency Evacuation with Dynamic Staff Coordination

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Abstract. We present a novel hybrid evacuation simulation framework that integrates Particle Swarm Optimization (PSO) with the Social Force Model (SFM) to model both intelligent path-finding and realistic crowd dynamics. Our system features dynamic staff coordination policies, multilayered behavioral modeling, enhanced door and exit queuing logic and, adaptive parameter tuning for emergency scenarios. The framework supports eight different evacuation policies, real-time 3D visualization, and comprehensive performance analytics. Experimental results demonstrate improved evacuation efficiency through intelligent staff–civilian coordination and adaptive swarm behavior.

Keywords: Crowd evacuation· Social Force Model (SFM)· Particle Swarm Optimization (PSO)· Staff coordination policies · Behavioral simulation

1 Introduction

Fire emergencies demand rapid and coordinated evacuations, where delays or poor design can be fatal. Incidents such as the Stardust fire in Dublin, where 48 people died due to blocked exits [7], highlight the importance of effective evacuation strategies.

Computational models support this goal. The Social Force Model (SFM) [3] simulates pedestrian interactions, while Particle Swarm Optimization (PSO) enables adaptive pathfinding under congestion and hazards [1]. However, existing approaches often overlook behavioral variability, staff coordination, and dynamic adaptation [5].

This paper introduces a hybrid PSO-SFM framework that integrates swarm-based decision making with physics-based movement, incorporates behavioral compliance and staff policies [8], and adapts parameters in real time. The framework is designed for complex multi-floor evacuations and aims to improve both simulation fidelity and practical safety planning.

While other optimization strategies such as Genetic Algorithms, Ant Colony Optimization, or Reinforcement Learning could be considered for evacuation

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routing, PSO provides several advantages for this context. First, PSO is computationally lightweight and supports continuous online updates, enabling real-time adaptation to evolving congestion and hazards without retraining. Second, PSO naturally supports decentralized decision processes, aligning with limited human situational awareness in emergencies. Third, PSO provides smooth directional updates, avoiding abrupt re-routing that would produce unstable or oscillatory motion when combined with SFM. These properties make PSO particularly suitable for time-critical, dynamic evacuation scenarios requiring both reactivity and stability.

2 Related Work

Evacuation studies frequently employ the Social Force Model (SFM) to simulate pedestrian dynamics and optimization methods such as Particle Swarm Optimization (PSO) to enhance efficiency. While SFM models interactions realistically, it adapts poorly to evolving hazards, motivating hybrid approaches that combine micro-level dynamics with macro-level optimization.

Jun et al. [5] applied an extended SFM with Moth-Flame Optimization for multi-floor evacuation, addressing staircase congestion but omitting staff coordination and behavioral diversity. Makmul et al. [6] introduced leader-based SFM under low-visibility smoke, showing the value of guided evacuation; however, these policies were not embedded within hybrid optimization frameworks.

Other contributions include panic contagion modeling [8] and smoke dispersion analysis [9], yet these remain isolated from staff dynamics or scalable optimization. Some studies focus on hazard propagation or building-specific case studies, but neglect heterogeneous populations or explicit staff policies. Our hybrid PSO-SFM framework integrates structural constraints, compliance dynamics, and adaptive staff coordination, bridging these gaps and providing a unified basis for comparative policy evaluation.

3 Hybrid PSO-SFM Framework

To improve clarity and structure, we group the core technical elements of our approach—agents, architecture, dynamics, and policies—within a single framework section.

3.1 Simulation Actors and Roles

The model defines two actor types: **civilians** and **staff**. Civilians represent general occupants with limited perception and reactive, local decision-making. They navigate based on visible congestion and exits but lack global knowledge of the environment.

Staff agents serve as informed guides with global awareness of exits, floor connectivity, and population distribution. Through policy-driven behavior, they influence nearby civilians and coordinate evacuations. Functioning as decentralized controllers, staff integrate local guidance with system-wide strategies, forming the basis for the hybrid PSO-SFM coordination.

Population Heterogeneity and Agent Variability To reflect a realistic occupant mix, civilians are partitioned into age and mobility groups. At initialization, each civilian is assigned to one of three age categories (youth, adult, elderly) and to a mobility class (normal or reduced). These attributes determine maximum walking speed, acceleration, and sensitivity to congestion. Elderly and mobility-impaired agents typically move at 40–60% of the nominal walking speed and require larger interpersonal distances, making them more vulnerable to bottlenecks.

Baseline simulations use a heterogeneous population with adults forming the majority and smaller proportions of elderly and reduced-mobility agents. Staff agents are modeled as physically able adults with higher compliance and full knowledge of exits and inter-floor connectivity.

To avoid deterministic behavior across runs, initial room assignments, age/mobility categories, and compliance parameters are sampled from fixed distributions at the start of each simulation. Thus, even when scenario-level parameters (e.g., total population, exit configuration) are held constant, individual agents behave differently across repeated simulations of the same scenario, supporting more robust policy comparisons.

3.2 Hybrid Algorithm Architecture

The hybrid PSO-SFM framework integrates three layers—strategic planning, operational coordination, and physical movement—enabling both high-level adaptation and realistic motion in multi-floor settings.

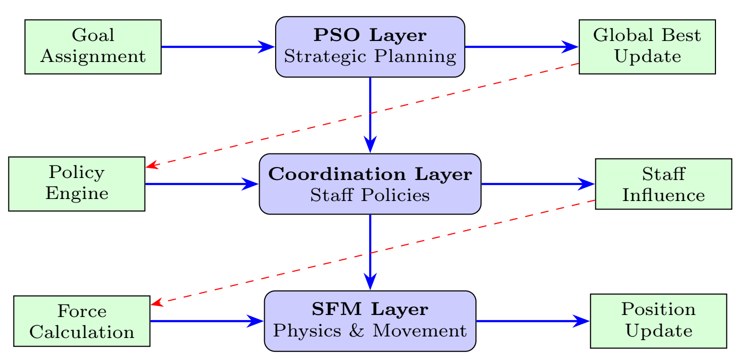

Fig. 1. Multi-layer PSO-SFM architecture with bidirectional data flow.

PSO Integration Strategy We adopt Particle Swarm Optimization (PSO) as the strategic decision-making layer because it aligns well with the dynamic characteristics of emergency evacuation. Unlike evolutionary approaches that require multiple generations to converge, or reinforcement learning approaches that depend on extensive prior training and reward shaping, PSO updates agent targets continuously through a weighted aggregation of personal best and shared global best experience. This enables rapid re-evaluation of exits, stairwells, and alternative routes as local density conditions change.

In our framework, PSO governs high-level goal assignment, while the Social Force Model (SFM) governs physical motion. Importantly, PSO outputs directional goals rather than direct velocity controls. This separation preserves the realism of SFM's movement dynamics while avoiding the erratic motion observed when optimization methods directly update velocities. Each agent maintains (i) a personal best exit or path segment and (ii) participates in a shared global best evaluation determined by congestion, distance, and floor connectivity.

Formally, PSO minimizes a scalar fitness function $f(g)$ for each candidate goal g:

$$f(g) = d(g) + \lambda\, \rho(g),$$

where $d(g)$ is the shortest-path distance from the agent's current position to g through the room connectivity graph, and $\rho(g)$ is an estimated congestion term proportional to the number of non-evacuated pedestrians associated with the rooms and doors on that path. We use $\lambda = 2.0$, consistent with the congestion-aware cost formulation described in Sec. 3.5. Lower values of $f(g)$ correspond to nearer, less crowded egress options, so the personal and global "best" goals are those that minimize this combined distance–congestion cost.

This decoupled architecture supports adaptive re-routing, allows independent tuning of strategic and movement-related parameters, and ensures stable pedestrian trajectories, even during rapid environmental changes. As a result, PSO contributes dynamic global coordination, while SFM ensures physically coherent local motion.

3.3 Dynamic Parameter Adaptation

Context-Aware PSO Parameters A fixed configuration of PSO parameters is often insufficient in dynamic emergency scenarios. Our framework supports **context-aware adaptation**, enabling agents to adjust inertia weight, cognitive, and social coefficients based on factors such as crowd density, urgency, and agent role.

SFM Force Balancing Agent motion is governed by the combination of driving, repulsion, and boundary forces. The driving force directs agents toward PSO-defined goals, repulsion enforces interpersonal avoidance, and boundary forces model interactions with walls and obstacles.

Staff Influence Implementation Civilian goals are computed as a blend of staff guidance and crowd-informed direction. The nearest staff target influences movement while crowd intelligence provides PSO-informed guidance. Simulations indicated that a blending factor in the range $[0.6, 0.8]$ achieves a good balance between stability and adaptability, with $\alpha = 0.7$ used as a practical trade-off. This formulation supports fluid transitions between staff authority and crowd influence, improving realism over fixed or binary staff-following models.

3.4 Staff Coordination Policies

Policy Framework Our system incorporates eight distinct staff coordination policies that simulate varying levels of assistance, prioritization, and situational awareness among trained personnel. Each policy reflects plausible real-world behaviors motivated by context-specific evacuation needs and informal or formal guidance from emergency planning practice and safety regulations [?,2].

- **All Evacuate** (`all_evacuate`): Staff evacuate immediately without assisting civilians, modeling scenarios where emergency responsibilities are unclear or absent.
- **All Assist** (`all_assist`): Staff remain until all civilians are evacuated, representing high-altruism environments like schools, nursing homes, or pediatric wards, where staff are expected to prioritize occupants over their own evacuation [2].
- **Half Assist** (`half_assist_half_leave`): Half of the staff assist civilians while the rest evacuate, balancing staff safety and civilian support in partially staffed settings.
- **Top Evacuation** (`top_evac`): Staff prioritize upper floors first, consistent with standard fire drill protocols in high-rise buildings or dormitories, where higher floors are often treated as higher risk [?].
- **Avoid Top** (`avoid_top`): Staff avoid the top floor and assist only lower levels, reflecting risk-aware behavior in unsafe upper areas (e.g., heavy smoke, structural compromise).
- **Assist Mobile First** (`assist_mobile_first`): Prioritizes able-bodied civilians to maximize throughput, suitable for stations or public events where rapid bulk clearance is a primary goal.
- **Assist Elderly First** (`assist_elderly_first`): Gives priority to elderly or mobility-impaired civilians, aligning with ethical and legal guidelines in healthcare facilities and accessibility legislation [?,2].
- **Zone Sweep** (`zone_sweep`): Staff are assigned spatial zones and systematically evacuate them, as practiced in airports, stadiums, or theaters, where wardens are allocated to specific blocks or sectors.

Multi-Staff Influence in Crowded Scenarios Challenging situations occur when multiple staff members occupy the same crowded room, attempting to guide the same set of nearby civilians. While basic leader election logic is used

Algorithm 1 Get Nearest Goal (Simplified)

```
Update ped.currentRoom from position
pos ← (ped.x, ped.y)
if staffAware then
    Determine optimal stair/exit goal based on floor and room
    Compute g_best from room pedestrians using evacuation heuristic
    return blended goal: 0.7 · staffGoal + 0.3 · g_best
else if isPSO then
    Determine target based on floor (exit if ground, stair otherwise)
    Find g_best from swarm in same room
    return PSO-optimized goal
else
    Use nearest stair or exit based on floor
    return basic goal
end if
```

to reduce redundancy, the behavioral model does not fully resolve conflicting guidance or overlapping influence fields. As a result, civilians may receive competing directional cues, potentially causing hesitation, indecision, or less efficient evacuation paths.

3.5 Behavioral Modeling Enhancements

To simulate realistic human behavior in multi-room environments, our framework enhances standard agent navigation with context-aware goal selection, congestion-sensitive pathfinding, and strict architectural constraints.

Optimal door selection is critical in multi-door layouts. Agents choose the most efficient exit based on distance, room connectivity, and dynamic congestion, reducing bottlenecks and enabling adaptive evacuation.

Architectural realism is enforced via a room connectivity graph that limits movement to doorways and stairwells. Pedestrians cannot traverse walls or unconnected spaces, and floor changes require stair use, preventing unrealistic behaviors such as clipping or teleportation.

Stair Movement and Transitions Stair movement is modeled using a step-based system:

- **Step Capacity**: Each stair step accommodates a limited number of pedestrians based on stair width and pedestrian radius.
- **Side-by-Side Positioning**: Pedestrians are assigned to the left or right side of each step depending on current occupancy.
- **Vertical Progression**: Floor-to-floor movement is discretized into individual steps, updating the z-coordinate incrementally.

Congestion-Aware Navigation A congestion-aware heuristic guides pedestrians to avoid densely populated areas, even if these are shorter routes. Navigation cost combines Euclidean distance with a dynamic crowd density penalty, reflecting real-world behavior where individuals steer clear of choke points, promoting even spatial distribution and reducing local bottlenecks.

The heuristic is defined as:

$$\texttt{cost} = d + \alpha \cdot \texttt{congestion}$$

where d is the distance to the goal, `congestion` counts non-evacuated pedestrians in the same room, and $\alpha = 2.0$ is the congestion penalty. This encourages agents to select less crowded paths when possible and is consistent with the PSO fitness formulation in Sec. 3.2.

Queue Management and Door Flow Modeling Effective evacuation simulation requires modeling realistic queue formation, bottlenecks, and flow regulation near doors and exits. Our framework uses a rectangle-based queueing system that enforces geometric constraints and behavioral rules.

Rectangle-Based Queue Zones Rectangular zones define queueing areas at exits and doors, providing clear spatial boundaries for pedestrian organization. The queue zone parameters are:

- **Queue Rectangle Length**: $L_q = 1.5 \times \text{DOOR\_WIDTH}$
- **Queue Rectangle Width**: $W_q = 1.6$ m
- **Maximum Pass Limit**: $N_{\max} = \left\lfloor \frac{\text{DOOR\_WIDTH}}{2 \times \text{PED\_RADIUS}} \right\rfloor$

Exit Queue Processing Door and exit queues are managed using a logical queue system:

1. **Queue Detection**: Pedestrians enter the queue upon reaching the designated rectangular zone.
2. **FIFO Processing**: Pedestrians are processed in first-in-first-out order based on arrival time.
3. **Throughput Limiting**: Only the first $N_{\max}$ pedestrians in the queue can evacuate per time step, preventing unrealistic flow through bottlenecks.

Door Queue Management Internal door queues operate per floor and follow similar principles:

- **Floor-Specific Processing**: Door queues are keyed by $(floor, door_x, door_y)$ tuples.
- **Reduced Repulsion**: Pedestrians in queues experience reduced social force repulsion (factor 0.2).
- **Velocity Damping**: Queue participants have their velocity reduced by a factor of 0.7 to simulate congestion.
- **Amplified Drive Force**: Pedestrians in queues experience increased driving force (factor 2.0) to reflect urgency.

4 Experimental Setup

4.1 Building Complexity and Realism

A common limitation in evacuation research is the use of overly simplistic building models. Many simulations are confined to single-story layouts without internal partitions, vertical movement, or realistic spatial constraints, reducing the applicability of their findings to real-world scenarios such as hospitals, offices, or event venues.

To address this, our experiments use a fully navigable three-story building with detailed internal structure and stairwells, enabling the study of route ambiguity, stairwell congestion, and multi-level coordination. This setup pushes evacuation simulation research beyond prior flat, single-floor models.

The environment is structured as follows:

- **Building Layout:** Three floors of 30×30 meters each, forming a symmetric square footprint typical of institutional or commercial facilities. Multi-floor movement via stairs requires coordinated decision-making.
- **Exits and Navigation Pathways:**
  - Two primary exits on the ground floor to support distributed flow.
  - Four internal staircases connecting floors, serving as key choke points for observing crowd merging and inter-floor coordination.
- **Real-Time Visualization:** A VPython-based 3D dashboard dynamically tracks individual and group behaviors, goal setting, and room-by-room clearance.

Figure 2 illustrates the three-floor building model, the placement of staircases and exits, and the staff–civilian interactions during evacuation.

5 Results and Discussion

5.1 Overall Performance Analysis

Figure 3 shows performance in fundamental evacuation scenarios. To improve legibility compared with earlier versions, we enlarge the composite visualization so that individual scenario panels and legends can be read more easily. The `Zone Sweep` and `Half Assist` policies consistently outperform others across wide stairs, single-room evacuations, and distributed populations, demonstrating the advantages of structured, collaborative strategies. The `Zone Sweep` policy achieves evacuation rates above 90% in most basic scenarios due to its systematic area coverage, ensuring no regions are neglected. The `Half Assist` policy shows strong versatility, with evacuation rates typically between 85–95%, balancing staff safety with civilian guidance effectively. In contrast, the `All Evacuate` policy underperforms, often below 60%, highlighting the critical role of staff leadership. Without informed guidance, crowd movement becomes inefficient and evacuation times increase significantly.

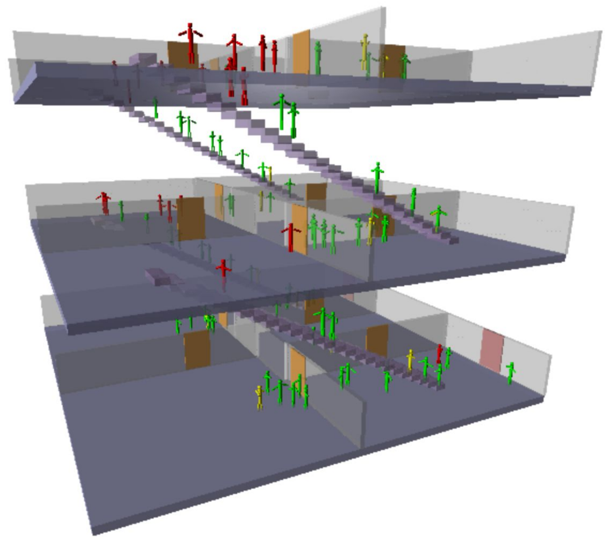

Fig. 2. Evacuation simulation in a multi-story building with three floors, internal staircases, and distributed exits. Red agents represent panicking civilians, and green agents denote staff with global awareness guiding civilians. This setup enables realistic analysis of congestion, stair bottlenecks, and inter-floor coordination.

Additional scenarios include blocked exits, immobile staff, family grouping dynamics, and malicious guidance, representing real-world evacuation complexities. Under blocked exits, the `Top Evacuation` policy excels, often achieving evacuation rates above 95%. Its strategy of clearing high-risk areas first ensures vulnerable populations are evacuated even when primary routes are compromised. The `Half Assist` policy remains robust across complex conditions, including immobile staff and family groupings. Partial staff allocation provides redundancy, maintaining effective guidance despite unavailable personnel.

Interestingly, in scenarios with malicious staff guidance, the `All Evacuate` policy outperforms assistance-based policies, achieving around 70% evacuation compared to 40–50% for staff-guided strategies. This suggests that no guidance may be preferable to incorrect guidance in certain conditions. Multi-staff influence limitations become pronounced in high-density areas, where overlapping influence zones and congestion amplify local noise, reducing directive effectiveness. While coordination algorithms perform well under moderate densities, their performance degrades in chaotic environments, highlighting opportunities for future work in decentralized coordination and conflict resolution among multiple staff agents.

Architectural factors, such as door width and floor layout, affected all policies, but `Half Assist` and `Zone Sweep` maintained an edge. Pedestrian char-

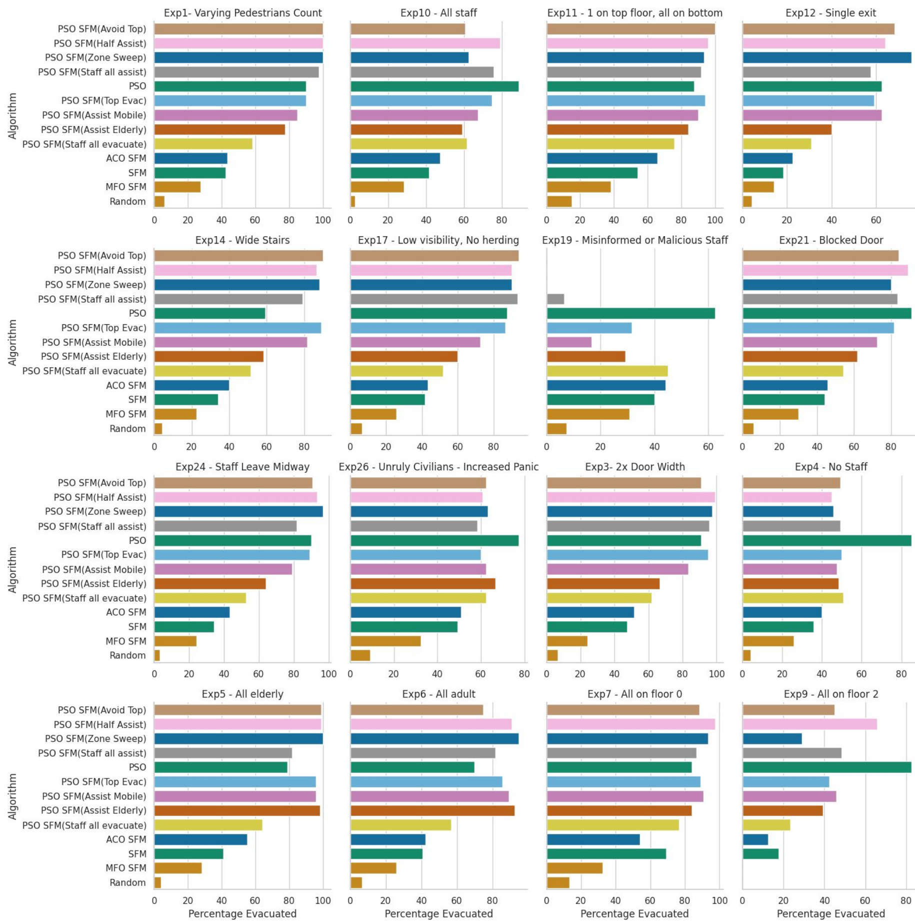

Fig. 3. Comparison of evacuation efficiency across experiments and algorithms. The figure summarizes 16 experimental scenarios; policies are ordered by average percentage evacuated in each scenario.

acteristics, including age and mobility, further emphasized the importance of assistance-oriented policies (`Assist Elderly`, `Zone Sweep`).

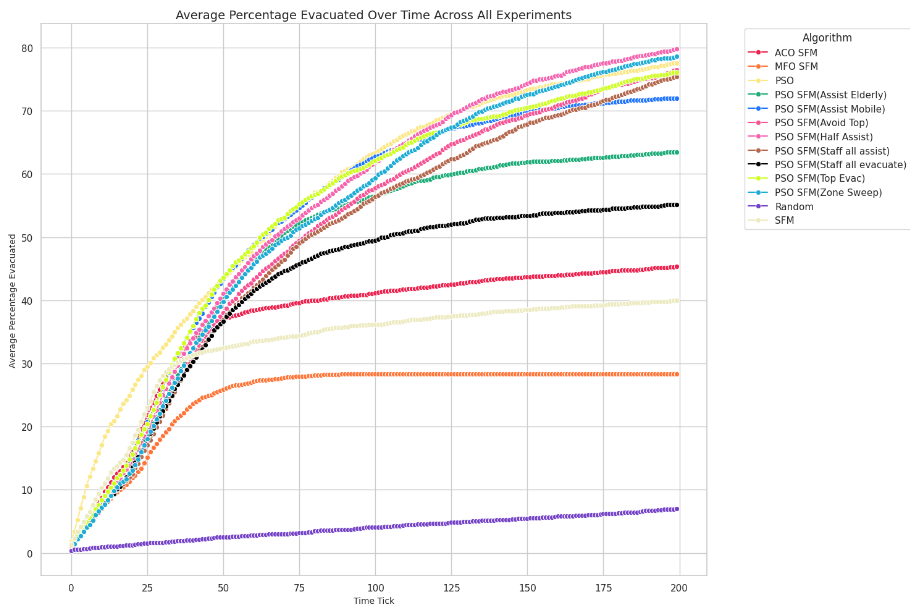

Fig. 4. Average evacuation performance of algorithms across all experiments. Curves report the mean percentage evacuated over time, allowing direct comparison of convergence speed and final performance.

While no single policy is universally optimal, experiments show that flexible, adaptive, and well-distributed strategies—especially `Half Assist` and `Zone Sweep`—provide the best balance of robustness and responsiveness. Strict policies like `Top Evacuation` excel in fire-focused scenarios, whereas strategies with spatial structure or partial staff autonomy perform consistently across diverse conditions.

Overall, the **PSO-SFM hybrid algorithms** outperform traditional methods (Random, SFM-only) across all scenarios, confirming the effectiveness of combining strategic planning (PSO) with realistic crowd dynamics (SFM).

6 Conclusion

This work presented a hybrid evacuation framework that integrates the Social Force Model (SFM) with Particle Swarm Optimization (PSO) to balance realistic pedestrian dynamics with adaptive, goal-directed decision-making. In our formulation, PSO governs high-level target selection while SFM controls continuous movement, enabling staff agents to coordinate civilians effectively without introducing unstable trajectories. The model supports heterogeneous populations, multi-floor navigation, and a suite of interpretable staff coordination policies that can be tuned to different operational or ethical requirements.

Across 25 experimental scenarios, results demonstrate that staff behavior plays a decisive role in evacuation performance. Structured and cooperative strategies, such as `Zone Sweep` and `Half Assist`, consistently improved evacuation rates and reduced bottlenecks, whereas policies lacking coordination (`All Evacuate`) produced markedly worse outcomes. These findings highlight the importance of organizational decision-making in emergency response, beyond purely physical or geometric considerations.

However, all simulations were conducted using a single three-storey building with a regular architectural structure. While this enabled controlled comparison across strategies, it also means that some performance observations may be conditioned by features of this layout. Strategies that perform well under balanced stair placement or symmetric exit distribution may behave differently in irregular or highly compartmentalized environments. Due to time constraints, testing across additional building models was not feasible, but the simulation framework is general and directly supports arbitrary floor plans. Future work will therefore focus on evaluating policy robustness across diverse architectural configurations.

In summary, effective evacuation outcomes depend not only on structural design and movement dynamics, but also on coordinated, informed, and ethically grounded staff behavior. The proposed PSO-SFM hybrid framework demonstrates how high-level decision policies can be embedded within realistic crowd simulations, providing a practical basis for training, planning, and safety analysis in real-world emergency management. The adoption of PSO is not solely based on optimization efficiency, but on its capacity to provide smooth, real-time adaptive goal selection that complements SFM's continuous movement dynamics in time-critical evacuation scenarios.

7 Ethical Considerations

Simulating emergency evacuations raises important ethical concerns beyond technical performance.

Staff prioritization policies, such as `Avoid Top` and `Top Evacuation`, create ethical dilemmas. While analytically efficient, they risk leaving vulnerable individuals behind, highlighting the tension between utilitarian outcomes and deontological duty.

Policies like `Assist Mobile First`, which favor faster pedestrians, may maximize overall evacuation rates but systematically disadvantage vulnerable populations, including the elderly, disabled, and families with children. These results underscore the need for ethically designed evacuation policies that do not disadvantage any group.

Legal frameworks, such as Irish legislation, mandate special provisions for vulnerable populations. Simulations demonstrate that algorithmic policies could inadvertently breach these responsibilities if unmonitored.

Finally, staff trust and competence are critical; roles like Fire Warden carry legal accountability and require regular training to ensure effective, ethical evacuation guidance.

8 Future Work

This research opens several avenues for extending the simulation framework to improve realism, adaptability, and practical utility.

First, incorporating detailed environmental features—such as smoke propagation, variable stair widths, blocked passages, and dynamic obstacles—will enhance scenario fidelity. Multi-hazard support, including combined fire, power loss, or flooding, will further improve planning relevance.

Second, richer psychological and social modeling—including panic contagion, fatigue, social ties, and memory-based decisions—will increase behavioral realism. Simulating diverse populations, such as elderly, disabled, or children, and accounting for cultural or ethical differences, will align the framework with accessibility and regulatory requirements [4, 2].

Third, advanced staff modeling, including dynamic task allocation, hierarchy, leader-following, and limited communication, would allow agents to respond intelligently under uncertainty or stress, better approximating real emergency operations.

Finally, integrating the framework into a decision-support dashboard with features like machine learning–driven policy recommendations, IoT-based rerouting, and floor plan integration could support emergency planners, fire marshals, and civil defense authorities in training and strategic planning, making the simulation actionable beyond academic research.

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Supplementary Materials

A.1 Video Demonstrations

Comprehensive demonstration videos of the simulation framework are available at the following links:

- Introductory overview video: https://youtu.be/7mYKR3q_eHA
- Full simulation walkthrough: https://youtu.be/QQfVgDCktDA

These videos illustrate multi-floor evacuation behavior, staff coordination dynamics, and adaptive PSO-SFM goal assignment in real time.

A.2 Code and Experiment Reproducibility

To support reproducibility and further analysis, we provide complete access to the simulation source code, configuration files, and all experimental results. The project repository is organized into structured folders corresponding to each experimental configuration, enabling clear traceability of results.

Repository: https://github.com/niveditha-vudayagiri/Fire-evac-PSO_SFM