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Data-Driven Evacuation Models: Bridging Biological Mimicry, Social Theory, and Intelligent Optimization – A Review

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Abstract: Managing crowd congestion during public events, daily urban activity, and emergencies remains a complex challenge, often exceeding the capabilities of conventional engineering and behavioral models. Current approaches rarely incorporate biological instincts or sociocultural dimensions, creating a critical research gap in understanding dynamic crowd responses. This paper introduces an interdisciplinary framework that combines biological mimicry, sociological theory, and advanced mathematical modeling to enhance evacuation strategies and crowd management. Drawing on animal behaviors observed during wildfires— such as evasive movement, strategic retreat, and post-fire resource exploitation—the study explores parallels in human responses under stress. Sociological insights further support the idea that human behavior is deeply influenced by evolutionary patterns and symbolic animal roles in society. The methodology integrates computational tools including the Social Force Model, game-theoretic simulations, and real-time optimization using algorithms like EVACNET+ and BFS-enhanced Dijkstra routing. Results demonstrate that biologically informed models improve predictive accuracy and adaptability in evacuation planning. Game-theoretic approaches reveal more realistic individual decision-making during congestion, while real-time optimization supports responsive route updates during hazards. These findings have direct implications for designing smarter, safer urban environments and emergency protocols. By bridging biology, sociology, and computational science, this paper offers a holistic path forward in managing dense human movement systems.

Keywords: Crowd congestion, biological mimicry, sociological modeling, social force model, evacuation optimization, predator-prey dynamics.

INTRODUCTION

Crowd congestion poses a major challenge [10] in cities, public events, and emergency situations, often causing restricted movement, safety risks, and increased stress. Traditional methods for managing crowd flow mainly depend on engineering solutions and simple behavior models. However, the increasing complexity of human environments requires more flexible and comprehensive strategies [9] .

This paper explores an interdisciplinary approach to understanding and mitigating crowd congestion, drawing inspiration from biological systems, ecological responses, sociological insights, and advanced mathematical models. Biological mimicry, a survival strategy in nature where organisms imitate others or their environment, offers valuable parallels for crowd behavior under stress. Animal responses to fire—such as strategic retreat, resource exploitation, and adaptive camouflage—highlight instinctual behaviors that can inform human evacuation planning [11].

Further, the sociological perspective emphasizes the deep-rooted connection between human and animal behavior [12], suggesting that understanding these parallels can enrich our interpretation of crowd dynamics. By integrating computational models such as the social force model, game theory-based simulations, and network optimization algorithms, this study provides a robust framework for simulating and improving evacuation outcomes.

Through this multidisciplinary lens, the paper aims to bridge gaps between biological insight, social behavior, and mathematical modeling, contributing to safer, smarter, and more responsive crowd management systems. The following sections discuss biological insights from mimicry and predator-prey dynamics, sociological perspectives on animal-human parallels, and advanced computational models for real-time crowd simulation and evacuation planning.

LESSONS FROM BIOLOGY, SOCIOLOGY AND MATHEMATICAL MODELING

Biological mimicry as the inception of the crowd congestion solution

Biological mimicry is a fascinating evolutionary strategy where an organism imitates the appearance and behavior of another species or its environment [13]. This adaptation enhances survival and reproduction by deceiving predators, prey, or potential mates. Mimicry is observed across various life forms, including insects, amphibians, birds, and plants. It reflects the complexity of evolutionary processes and ecological interactions, playing a crucial role in shaping the behavior and morphology of species [1]. Many animals have adapted to fire-prone environments, exhibiting behaviors that allow them to avoid danger or even benefit from fire events. Small mammals like cotton rats and rabbits were observed evacuating or relocating young in advance of fires, while large mammals such as deer and elephants typically avoid flames without panic. Birds and insects often exploit fires, flocking to burned areas to prey on exposed organisms. Notably, some predators— including hawks and certain beetles— are attracted to fire, using it to their advantage in locating food or nesting sites. The paper[2] also discusses behavioral adaptations like camouflage on burnt ground and the ecological role of fire in shaping animal communities. Animals are not just background elements but play active roles in shaping language, culture, social norms, and institutions. Through vivid examples—from idioms saturated with animal imagery to legal codes regulating animal-related crimes—Bryant illustrates how deeply embedded animals are in human social life. He explores a wide spectrum, including animals as surrogate humans, work partners, crime victims, and even social deviants. Particularly notable is his discussion of animals in symbolic, economic, and emotional roles, challenging sociologists to reevaluate the anthropocentric lens through which they study society. The paper also outlines emerging research directions, including the study of animal-related deviance, labor, and the ideological clashes over animal rights. Bryant's call [3] to action is clear: sociology must integrate the "zoological connection" to fully comprehend human behavior. By bringing animals into the sociological discourse, the paper opens up rich avenues for interdisciplinary research and a deeper understanding of societal values, identities, and structures. This work remains a foundational critique and a visionary appeal for a more inclusive and comprehensive sociology.

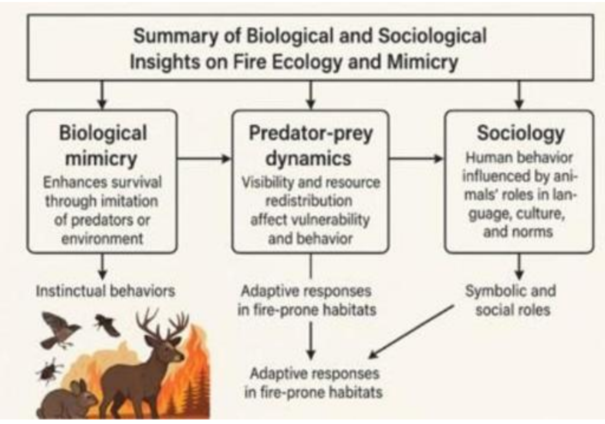

Fig. 1. Biological and social foundations of Crowd behavior

The authors [4] explore how fire-induced changes in habitat structure, visibility, and resource availability affect both predators and prey. Predators may be attracted to recently burned areas due to increased prey visibility and access, while prey species may experience increased vulnerability due to reduced shelter. The paper introduces a conceptual framework based on predation risk theory, identifying factors such as encounter rates, escape probability, and time exposed to danger. It discusses behavioral adaptations of prey, including changes in movement, habitat use, and cryptic coloration to evade predation. The study highlights that fire can amplify or buffer predation impacts depending on species traits and fire characteristics like severity, frequency, and timing. Fig. 1 emphasizes the complexity and context-dependence of these interactions, advocating for integrated fire and predator management in conservation strategies. The review concludes with key research gaps, such as the need for long-term data collection across diverse taxa and ecosystems, and a deeper understanding of how changing fire regimes under climate change will reshape predator–prey relationships.

Mathematical modelling of escapes ranging from particle to people.

Mathematical modeling of evacuation involves using equations and algorithms to simulate how people move and make decisions during emergencies. Models like the social force model represent individuals as particles influenced by virtual forces such as attraction to exits and repulsion from other people or obstacles. Game theory models simulate decision-making under competition for exits, aiming to minimize personal escape time. These models incorporate variables like speed, crowd density, and environmental layout. By solving equations such as Langevin dynamics or network flow equations [14], researchers can predict evacuation times, congestion patterns, and optimize building layouts for safer and faster evacuations.

The model [5]simulates evacuees as participants in a game where each strives to minimize personal evacuation time, taking into account the dynamic strategies of others. By computing a mixed-strategy Nash equilibrium, the model captures realistic decision-making processes and congestion effects. The paper further integrates this model into the SGEM (Spatial-grid evacuation model), demonstrating that evacuee interaction significantly affects evacuation patterns and total clearance time. Through simulation, the authors show improved flow distribution and reduced congestion compared to conventional models. This game-theoretic approach accounts for competitive behavior and adapts dynamically to environmental stimuli, making it especially suitable for high-density enclosures.

Social force model [6]introduces a physics-inspired framework to model pedestrian behavior through

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the concept of "social forces." Unlike actual physical forces, these are metaphorical representations of internal motivations that drive pedestrian movements. The model integrates multiple behavioral factors including acceleration towards a desired speed, repulsion from other individuals and obstacles, and attraction to specific points or people. Pedestrians are modeled using nonlinearly coupled Langevin equations, capturing realistic behavioral variability and randomness. The authors demonstrate that pedestrian behavior can be largely automatic in familiar situations, allowing it to be effectively described with deterministic equations. Through simulations, the model successfully replicates key real-world phenomena like lane formation in opposing flows and oscillatory movement patterns at narrow passageways, showing that complex crowd dynamics can emerge from simple interaction rules. The study is significant for urban planning and crowd management as it provides a computational tool that accurately simulates crowd behavior under various scenarios [15]. Furthermore, the authors suggest future extensions of the model to more complex social interactions and decision-making processes. See Table 1 for the comparison of the modelling techniques.

Recent interdisciplinary efforts have enhanced the realism and reliability of crowd simulation models by integrating behavioral psychology, computational fluid dynamics, and agent-based modeling. A hybrid approach [21] has been introduced that links the Social Force Model (SFM) with the Lattice Boltzmann Method to simulate indoor airflow and pollutant dispersion, accounting for the influence of human motion during evacuation. This method enables more accurate environmental hazard assessments during emergencies. A comprehensive review [22] has examined how social behavior and communication are treated in agent-based evacuation simulations. They noted that many existing models underrepresent group influence, shared decision-making, and dynamic information exchange, which are critical for simulating realistic evacuation outcomes. The impact of physical interactions in SFM, particularly the role of body force in different architectural layouts, has been evaluated [23]. Their work demonstrated that the same model parameters may produce varying effects based on spatial context—enhancing flow in bottlenecks while hindering it in corridors. The SFM has been expanded by embedding stress-response theory [24], enabling the simulation of psychologically-driven behaviors like urgency, discomfort, and proximity aversion during hazardous conditions such as fires.

Table 1. Comparative Overview of Evacuation Modelling Technique

Aspects	**Social Force Model**	**Game Theory Model**	**Mathematical Foundations**
Conceptual basis	Individuals are modelled as particles with "social forces".	Individual models as strategic agents competing for exits.	Uses differential equations, optimization, and graph theory.
Key influences on agents	Attraction to exit, repulsion from others/obstacles, personal space.	Personal time minimization and strategies of other agents.	Network flow models, Langevin dynamics, Dijkstra algorithm.
Mathematical tools used	Langevin equations (non-linear, stochastic dynamics).	Game theory (Nash equilibrium), spatial grid modelling.	Predictive modelling of flow, path optimization.
Behaviors Captured	Lane formation, oscillatory flow at bottlenecks, and automatic movement in known spaces.	Competitive decision making, interaction effects on evacuation.	Provides a foundation for real-time optimization and scenario planning.
Application	Urban planning, crowd management, event simulation.	Emergency evacuations in buildings, high-traffic zones.	Infrastructure design, hazard response planning.

Real-Time Evacuation Optimization

Optimization techniques involve mathematical models to determine the best possible solution within given constraints [16]. There are different types, including linear, nonlinear, discrete, and stochastic optimization, each suited to specific problems. The optimization approach in the EVACNET+ program [7] provides a vital framework for minimizing building evacuation time during emergencies. By modeling a building as a capacitated network—where nodes represent spaces (e.g., rooms, halls, stairwells) and arcs represent passageways—EVACNET+ applies a specialized network flow transshipment algorithm to calculate the most efficient evacuation plan.

It identifies the optimal distribution and routing of evacuees through the building to exit points, reducing delays and congestion. By analyzing arc capacities and traversal times, the system pinpoints choke points where movement slows, guiding interventions like infrastructure redesign or adjusted crowd control. An offline evacuation network[8] is established using the Dijkstra algorithm to compute optimal paths from all building nodes to exits under normal conditions. This serves as a foundation for pre-planned routes.

When a fire or blockage occurs, however, the real-time situation may render the precomputed paths unsafe [17]. To address this, the online phase employs a Breadth-First Search (BFS) strategy focused on local updates around hazard zones [18]. This dynamic adaptation avoids affected nodes and recomputes paths quickly, leveraging the existing offline network to reduce computational load.

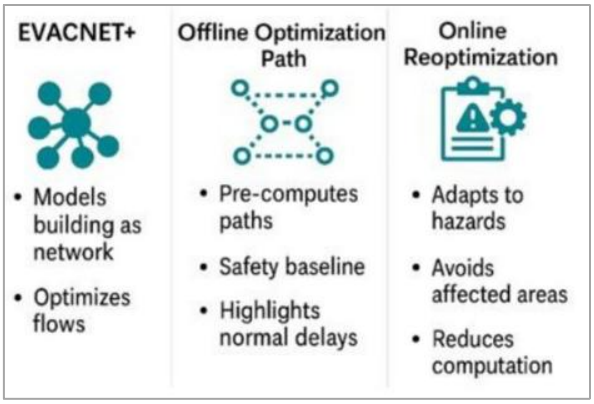

Fig. 2. Optimization approaches for improving evacuation efficiency

This uses a macroscopic graph-based model to represent buildings and simulates various emergency scenarios. Experimental results on a large-scale shopping mall layout show that this hybrid approach balances speed and accuracy better than traditional algorithms like Dijkstra alone [19], particularly when facing rapid topology changes due to hazards. Overall, the study Fig. 2 demonstrates how integrating real-time information and localized re-optimization can enhance evacuation effectiveness and responsiveness in emergencies [20].

DISCUSSION

Introduction to integration

Integrating biological mimicry, social theory, and optimization creates a multidimensional framework for modeling complex systems like crowd evacuation. Biological mimicry offers decentralized movement strategies inspired by nature—such as ant colony pathfinding and flocking behavior—which enable agents to navigate dynamically and adaptively. Social theory adds depth by incorporating human behavior, including panic responses, trust dynamics, and role-based actions. These elements ensure that simulations reflect realistic decision-making and interpersonal interactions. Optimization techniques refine the system by balancing competing objectives like minimizing evacuation time, reducing congestion, and enhancing safety. Algorithms such as genetic optimization or particle swarm methods can adaptively tune parameters and guide agents toward efficient outcomes. When combined, these domains form a layered architecture, see Table **2**. Agent-based modeling serves as an ideal implementation platform, allowing each agent to operate with biologically inspired motion, socially informed decisions, and optimized strategies. This integrated approach supports the development of resilient, scalable, and context-aware evacuation models. It also enables planners to simulate diverse scenarios, test interventions, and design adaptive infrastructures. Ultimately, this synthesis bridges natural systems, human dynamics, and computational intelligence to address real-world challenges in safety-critical environments.

Table 2. Contributing Layers and their function

Layer	Function
Biological	Movement rules
Social	Behavioral realism
Optimization	Performance tuning

Benefits of integration

The study finds that integrating biological mimicry, sociological insights, and advanced mathematical models. Fig. 3, enables realistic simulations and adaptive strategies for safer, efficient, and context-sensitive crowd congestion and evacuation management. Animal behaviors during environmental stressors like fire— such as strategic retreat, resource optimization, and adaptive camouflage—can inform human crowd movement and evacuation planning. Human-animal behavioral parallels and the symbolic roles of animals in culture highlight the importance of considering sociocultural factors in crowd behavior and emergency response. Models like the social force model, game-theoretic simulations, and network flow algorithms effectively capture individual and collective behaviors in evacuation scenarios.

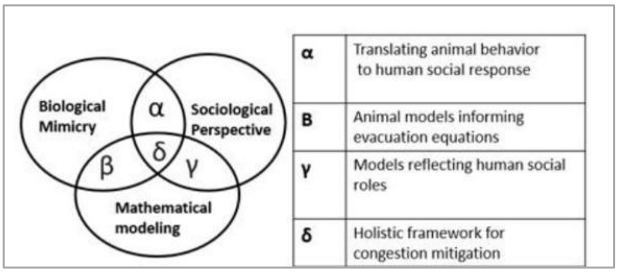

Fig. 3. Interdisciplinary support function benefits

By modeling evacuees as strategic agents competing for exits, game-theoretic approaches improve predictions of congestion and individual decision-making under pressure. Tools like EVACNET+, Dijkstra's algorithm, and real-time BFS-based re-routing minimize evacuation time and adapt to changing hazard conditions.

Limitations and Future Directions

While evacuation modeling has evolved considerably, key integrative gaps persist across theoretical and applied domains. Agent-based approaches and social force models often operate in silos, limiting their ability to capture the nuanced interplay between individual decision-making and emergent crowd

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behavior. Moreover, interdisciplinary efforts—drawing from sociology, biology, and computational sciences—frequently struggle to translate conceptual insights into actionable strategies aligned with real-world emergency protocols. These challenges are compounded by limited access to high-resolution empirical data, the computational demands of simulating large-scale heterogeneous populations, and the inherent unpredictability of human behavior under stress. Addressing these issues requires a multi-pronged strategy: leveraging sensor networks and crowd-sourced data to enrich empirical baselines; adopting scalable algorithms and parallel computing frameworks to manage computational loads; and incorporating probabilistic behavioral models and adaptive learning techniques to better capture variability in human responses. Without such integrative and technically grounded solutions, the development of unified frameworks capable of informing both predictive modeling and operational planning will remain constrained, underscoring the urgent need for more cohesive, context-sensitive integration across disciplines and scales

CONCLUSION

Tackling the challenges of crowd congestion requires insights drawn from multiple fields. By observing how animals instinctively respond to threats like fire, researchers can adapt these behaviors to improve human evacuation strategies. Sociological theories bridge the gap between species, highlighting behavioral similarities that shed light on human movement in crowded scenarios. Mathematical modeling—spanning tools like social force dynamics, game-theoretic strategies, and optimization frameworks—adds predictive power and flexibility to planning efforts.

The fusion of these diverse perspectives lays the groundwork for innovative solutions to managing densely populated environments. Future studies should continue refining this integrated approach to deliver responsive, real-time systems tailored to dynamic emergencies and evolving urban landscapes.

This review departs from traditional survey papers by offering a nuanced and interdisciplinary synthesis of vacuation modeling, drawing from game theory, social force dynamics, and optimization strategies. Rather than merely cataloging existing methodologies, it critically examines their conceptual foundations, operational limitations, and contextual relevance. The proposed integrative framework not only bridges methodological silos but also enhances the practical utility of these models in real-world crowd management and emergency response scenarios. Through structured comparisons, scenario-based evaluations, and a forward-looking research agenda, this paper aims to serve as both a comprehensive reference and a catalyst for future advancements in the field

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