Swarm Intelligence Applications for Emergency Evacuation Planning: A State-of-the-Art Survey

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Introduction

Global Impact of Natural Disasters (2022)

Catastrophic Events

380+

↑ Increasing frequency trend

Natural catastrophic events recorded worldwide, including Extreme weather events, Hydrometeorological disasters, Geological events, Climate-related catastrophes

Human Impact

30,000+

↑ Significant increase in casualties

Deaths recorded from climate and hydrometeorological events: Heatwaves, Floods, Storms, Other weather-related disasters

Economic Impact

$223B

↑ Rising economic costs

Total economic damages from: Infrastructure damage, Business interruption, Recovery operations, Long-term economic effects

Complexity of Emergency Evacuation:

- Growing need for robust evacuation strategies due to increasing disaster frequency
- Requires managing uncertainties in human behavior and infrastructure.
- Involves optimizing routes, resource allocation, and traffic flow.
- Necessity for scalable solutions to handle large-scale evacuations
- Critical importance of protecting vulnerable populations
- Need for cost-effective and efficient evacuation planning methods
- Importance of region-specific adaptation strategies

Why Swarm Intelligence?

- Inspired by collective behaviors (e.g., ants, birds, fish).
- Algorithms like PSO, ABC, and ACO excel in:
  - Dynamic decision-making.
  - Addressing large-scale evacuation scenarios.
  - Iteratively improving solutions under constraints.

Methods

Optimization Approaches for Emergency Evacuation:

Exact Approaches

Characteristics:

- Optimal solutions guaranteed
- Mathematical precision
- Complete search of solution space

Limitations:

- Fails with large-scale problems
- Computationally intensive
- Not practical for real-time scenarios

Heuristic Algorithms

Characteristics:

- Good-quality solutions
- Reasonable computation time
- Practical implementation

Challenges:

- Effectiveness varies in real-life scenarios
- May not find optimal solutions
- Needs further research validation

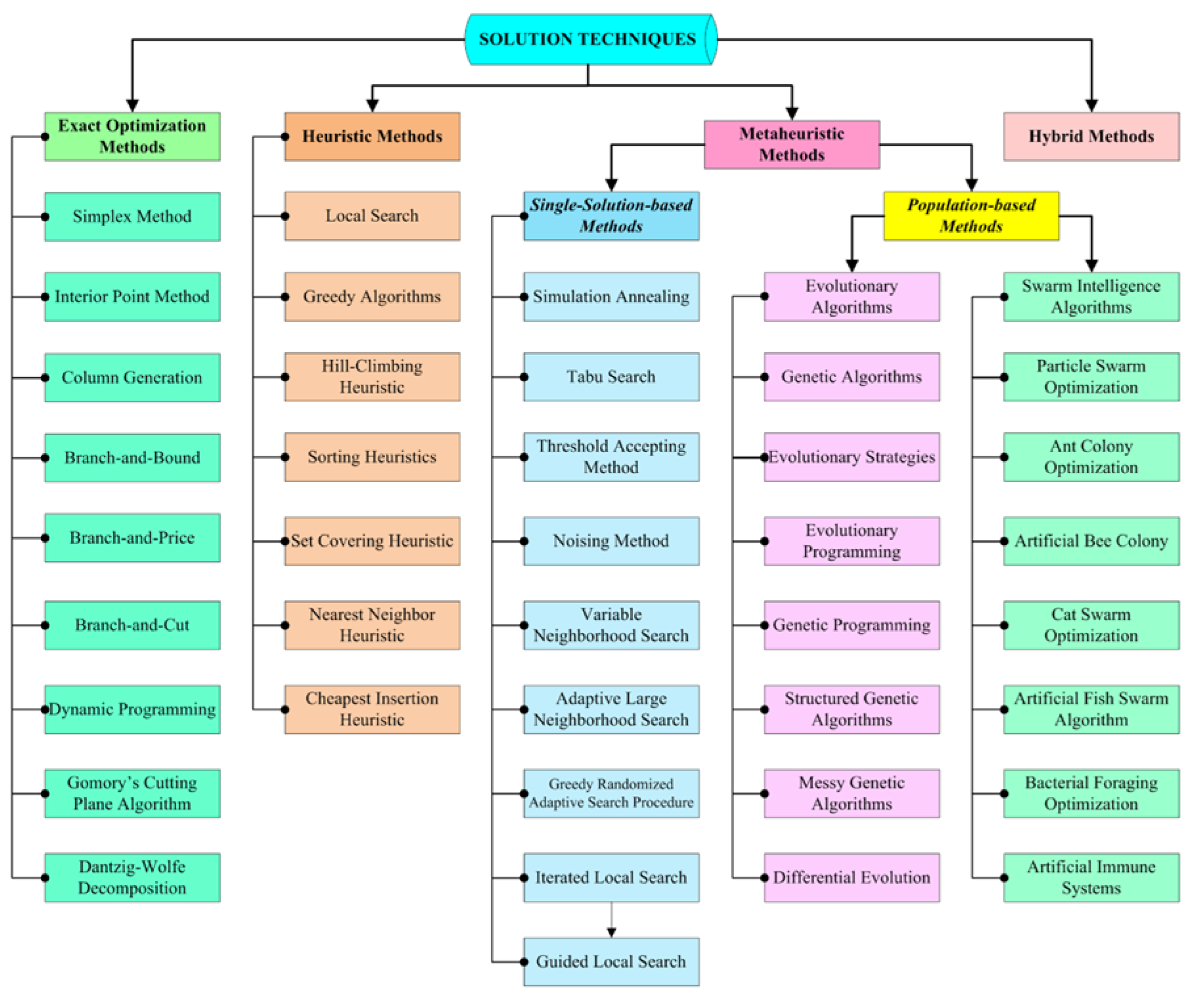
Metaheuristics

Characteristics:

- Bio-inspired strategies
- Balance solution quality and computation
- Advanced optimization capabilities

Types:

- Artificial Neural Networks
- Evolutionary Algorithms
- Swarm Intelligence



Classification of optimization solution techniques.

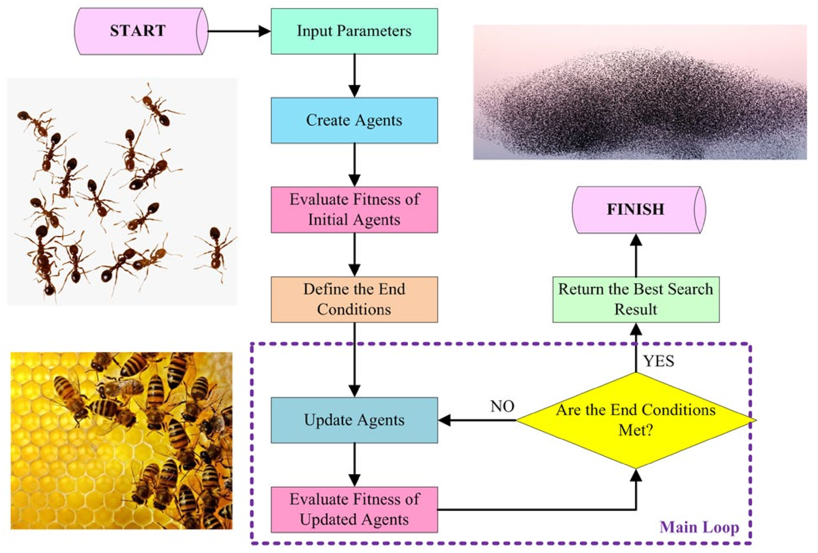
Swarm Intelligence Algorithms

Key Features

- Mimics natural self-organized behaviors
- Uses collaborative population search
- Applies probabilistic rules
- Evolves solutions over iterations
- Surpasses traditional techniques

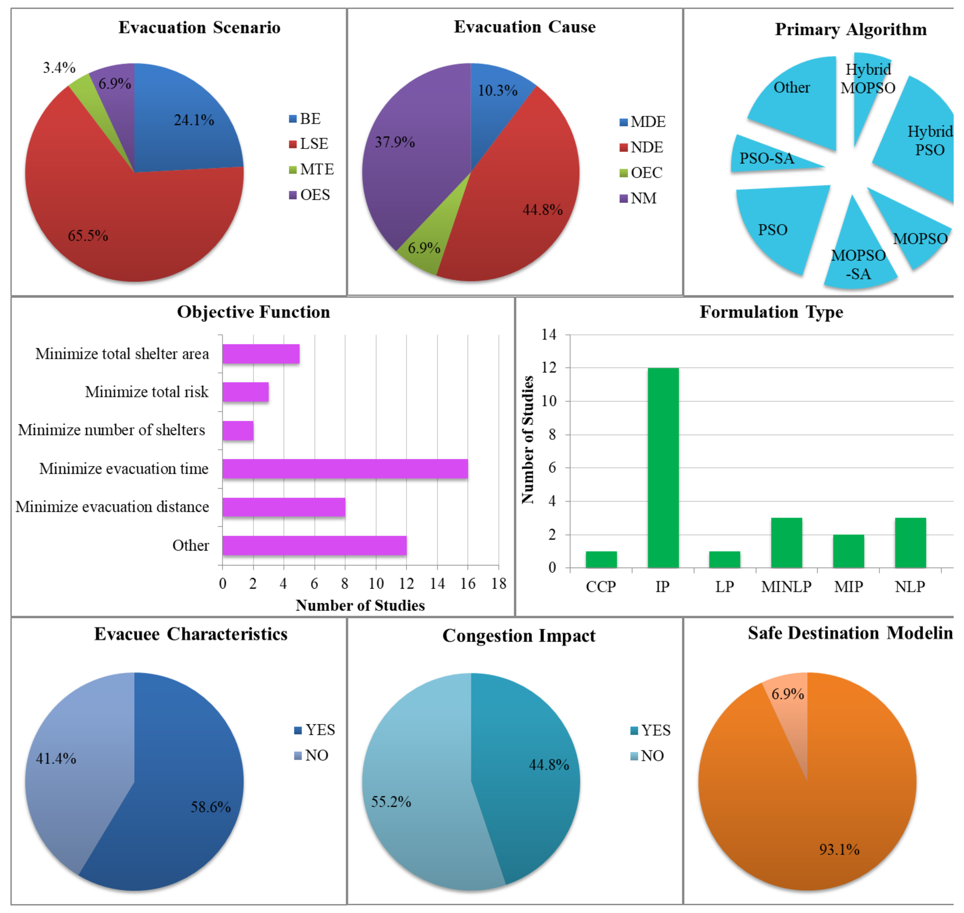
Focus Areas

- Particle Swarm Optimization (PSO)
- Artificial Bee Colony (ABC)
- Ant Colony Optimization (ACO)
- Solution encoding schemes
- Custom algorithmic operators
- Hybridization procedures



PSO Applications in Emergency Evacuation Planning

- 65.5% of studies addressed large-scale evacuations.24.1% focused on building evacuations. Mixed traffic and niche scenarios (e.g., ship evacuations) received minimal attention
- .Evacuation Causes: Natural Disasters (44.8%): Earthquakes, floods, typhoons. Manmade Disasters (10.3%): Fires, toxic gas releases.



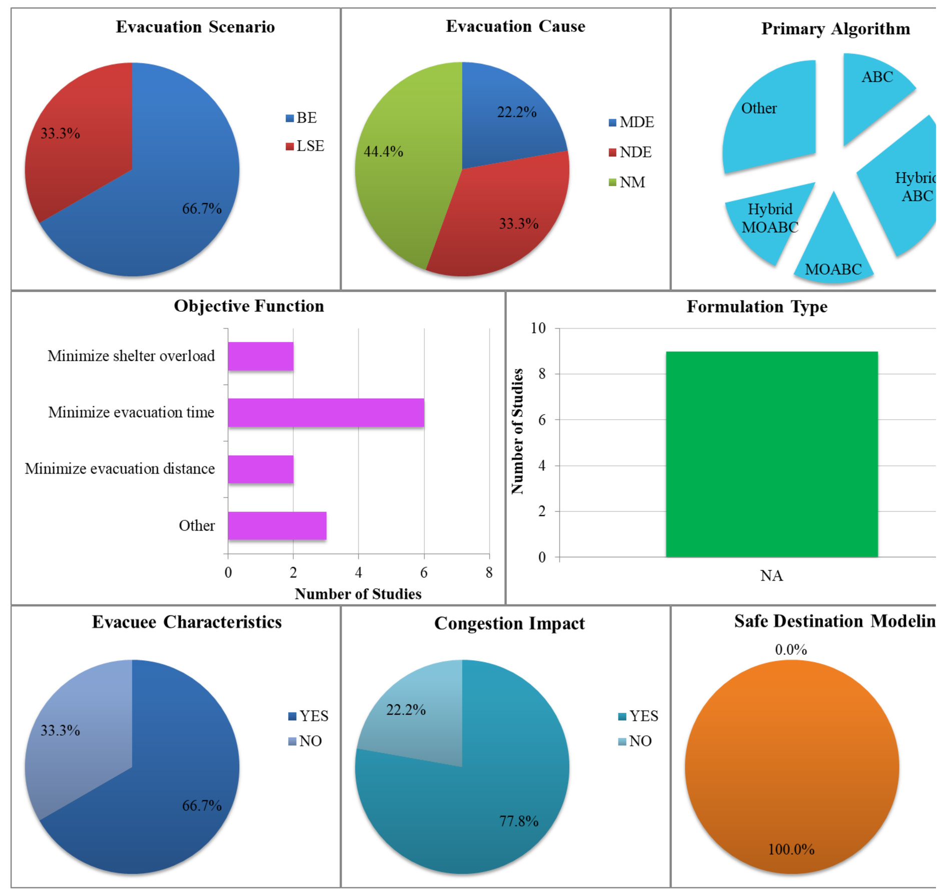
Innovations in PSO:

- Hybridizations with other novel Metaheuristics.
- Custom mechanisms to improve convergence.
- Behavioral modeling using the Social Force Model.

Future Research Opportunities:

- Dynamic PSO Models: Incorporate multi-stage optimization for evolving events.
- Behavioral Complexity
- Hybridization: Explore integration with newer algorithms like Grey Wolf Optimizer, Salp Swarm Algorithm, and Red Deer Algorithm
- Scalability & Efficiency

ABC Applications in Emergency Evacuation Planning



Innovations in ABC:

- Behavior Modeling
- Multi-Population Frameworks
- Custom Search Strategies

Future Research Directions

- Uncertainty Modeling: Incorporate stochastic approaches to handle uncertain evacuee behavior, hazard dynamics, and capacity limitations.
- Customized Operators: Leverage genetic operators like crossover and mutation to improve solution diversity and algorithm robustness.
- Multi-Population Algorithms
- Adaptive Mechanisms
- Real-World Applications

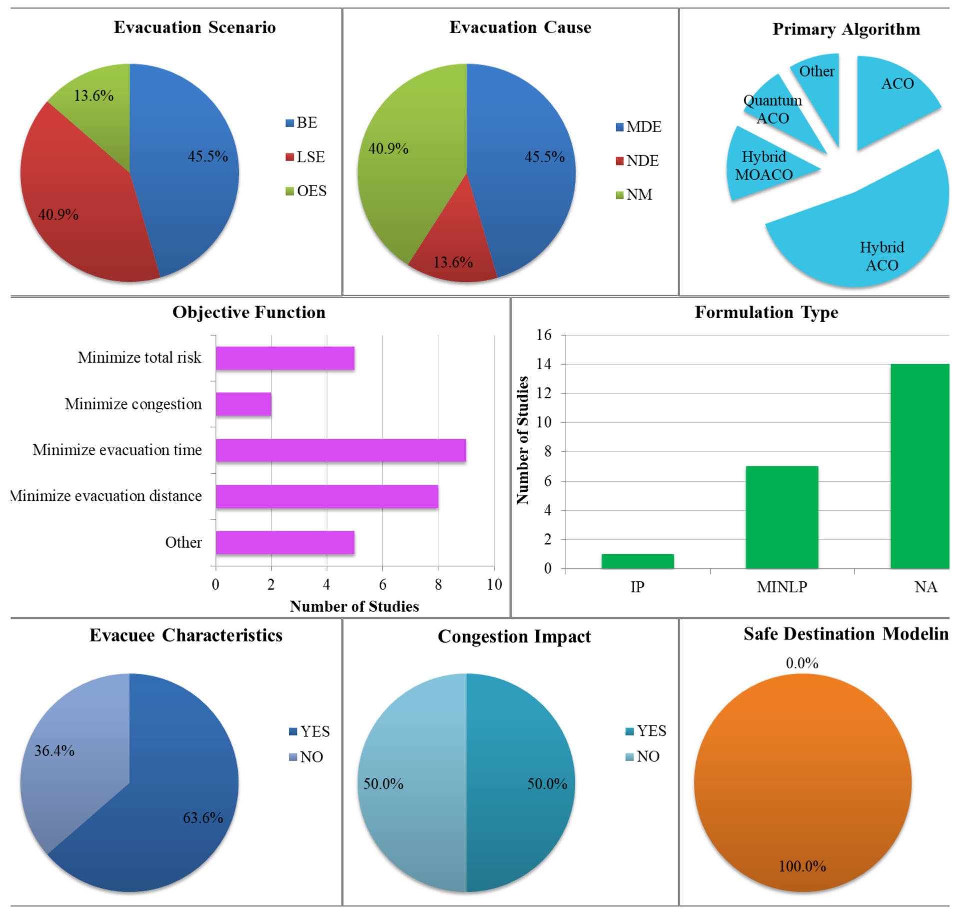
ACO Applications in Emergency Evacuation Planning

Applications by Scenario: Building Evacuations (45.5%), Large-Scale Evacuations (40.9%).

Evacuation Causes: Manmade Disasters (45.5%). Natural Disasters (13.6%)

Innovations in ACO:

- Hybridization (54.5%): Integration with genetic algorithms, quantum theory, and fire dynamics simulators.
- Elite Ants: Pheromone-based convergence for efficient pathfinding.
- Tabu Search: Improved search efficiency by avoiding repetitive paths.
- Dynamic Parameters: Adjusting for fire, toxicity, and visibility in path optimization.



Conclusion

- Disasters are increasing in frequency and severity, threatening lives and infrastructure.
- Advanced strategies for emergency evacuation planning are more critical than ever.
- Swarm intelligence algorithms (e.g., PSO, ABC, ACO) offer powerful tools for addressing these challenges.
- PSO and ABC excel in large-scale and building evacuations (natural disasters like earthquakes and floods). ACO is widely used for manmade disasters (e.g., fires, toxic spills).
- Hybridization with genetic algorithms, simulated annealing, and novel approaches (e.g., emperor penguin colony).
- Behavioral modeling using social force frameworks and elite-ant pheromone mechanisms.
- Lack of nuanced behavioral and congestion modeling.
- Limited focus on uncertainty and mixed traffic evacuations.