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Dynamic Path Optimization and Personnel Scheduling for Building Emergency Evacuation

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Abstract:

Modern buildings feature complex layouts, high occupancy, and mixed functions, making indoor safety inspections critical for emergency evacuation. Traditional inspection strategies rely heavily on experience, often leading to unreasonable paths, missed checks, and delayed evacuation—especially in smoky, low-visibility environments. Existing studies lack an integrated framework that combines standardized sweep protocols, realistic constrained path modeling, and multi-story collaborative scheduling. This paper develops a full-chain emergency evacuation sweep system. For single-floor scenarios, we model multi-responder cooperative inspection as an Open Multiple Traveling Salesman Problem with Permanent Forbidden Edges and Allowed Revisits (OMTSP-PFE-AR) and solve it using a greedy algorithm. For multi-story composite buildings, a bi-level optimization model is proposed to separate intra-floor scheduling from global personnel configuration. Experiments on a single-story office building and a three-story mixed-use building show that the proposed method achieves full inspection coverage with balanced workloads, shorter sweep times, and lower overall costs. The system adapts to both normal and heavy-smoke conditions, supports professional role matching, and improves the safety and efficiency of real-world building emergency evacuation operations.

Keywords: Emergency evacuation; Building safety; OMTSP-PFE-AR

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1. INTRODUCTION

Modern urban buildings are characterized by complex spatial layouts, high occupancy densities, and diverse functional combinations. In emergencies such as fires and toxic gas leaks, rapid and thorough indoor safety sweep inspections directly determine evacuation efficiency and occupant survival [1,2].

Traditional room-by-room inspection approaches rely heavily on empirical operation, which frequently leads to irrational path planning, delayed responses to high-risk areas, and high rates of missed checks. According to 2023 data from the National Fire Protection Association (NFPA), approximately 30% of building emergency evacuation delays are caused by inefficient sweep strategies and insufficient priority handling of critical zones [3]. In harsh environments with heavy smoke, furniture obstruction, and limited visibility, conventional methods perform even worse and can hardly meet emergency safety requirements.

In recent years, mathematical optimization and intelligent algorithms have been increasingly applied to emergency response systems [1]. Gendreau et al. reviewed dynamic routing models for emergency services and emphasized the importance of real-time constraints and multi-objective coordination [1]. Helbing & Molnár established the social force model to describe pedestrian movement dynamics during evacuation [2]. Blum et al. summarized metaheuristic algorithms for combinatorial optimization problems, providing a solid methodological foundation for solving NP-hard path planning problems [4]. Wang et al. integrated environmental perception techniques to support real-time monitoring and path planning for indoor emergency evacuation [5]. Nevertheless, existing research still lacks a systematic framework that unifies standardized sweep protocols, realistic constrained path modeling, and multi-story collaborative scheduling.

To fill these gaps, this study establishes a comprehensive emergency evacuation sweep system. The multi-responder cooperative sweep problem is formulated as the Open Multiple Traveling Salesman Problem with Permanent Forbidden Edges and Allowed Revisits (OMTSPPFE-AR) to capture realistic constraints including fixed exit rules and visibility attenuation. For multi-story composite buildings, a bi-level optimization model is designed to decouple intra-floor scheduling and global personnel configuration. The proposed framework provides theoretical support and practical solutions for improving the safety and efficiency of emergency sweep operations in complex buildings.

2. RELATED WORK

A. Emergency Path Planning

Emergency path planning has been widely studied based on graph theory and combinatorial optimization. Traditional shortest-path algorithms are insufficient for multi-responder collaboration and complex constrained environments [1,4]. The multiple traveling salesman problem (MTSP) provides a basic structure for multi-agent inspection tasks, yet most formulations ignore real-world constraints such as fixed start–end exits and visibility reduction caused by smoke or obstacles, which greatly limits their practical applicability [4].

B. Multi-story Scheduling and Personnel Allocation

Multi-story building emergencies require coordinated cross-floor scheduling and professional responder matching. Existing studies often focus only on single-floor path optimization and lack hierarchical optimization mechanisms that integrate task scheduling and personnel configuration [5,6]. Such simplifications lead to unbalanced workload distribution and capability mismatch in actual emergency deployment.

C. Dynamic Emergency Decision Making

Most existing studies focus on partial components of emergency response rather than constructing a full-link sweep system that covers inspection criteria, multi-person collaboration, and multi-floor coordination. Few models support differentiated strategies for vulnerable groups and functional zoning, making it difficult to achieve reliable and standardized sweep operations in real scenarios.

3. METHODOLOGY

A. Standardized Emergency Evacuation Sweep System

1) All-Clear Criteria: A region is confirmed safe only after four steps: visual scanning, calling and listening, life detector detection, and re-sweep verification. High-risk areas require double checks.

2) Occupant and Building Classification: Occupants are divided into vulnerable groups, adolescents, and adults. Buildings are divided into residential, daycare/nursing home, office, and warehouse types to support targeted strategies.

3) Responder Deployment and Redundancy: Responders include firefighters, medical staff, security, engineers, and caregivers. Three redundancy mechanisms (personnel, method, path) are designed to improve reliability.

4) Emergency Classification: Emergencies are divided into hazard-spread type (fire, gas leaks) and structural-instability type (cracks, deformation), with differentiated response strategies.

B. Single-Story Sweep: OMTSP-PFE-AR Model

For a single-story office building, this study proposes a two-person cooperative emergency evacuation inspection path optimization model, formulated as OMTSP-PFE-AR. The problem is modeled as an undirected weighted graph, where inspection points and safe exits are defined as vertices. Manhattan distance is adopted as edge weights to represent actual movement costs under wall obstructions. The optimization objective is to minimize the maximum total inspection time of the two responders, including both travel time and first-visit inspection time. The model satisfies key constraints: full coverage of all inspection points, path continuity, exit-only start/end restrictions, obstacle-induced permanent forbidden edges, and node revisits without additional inspection costs.

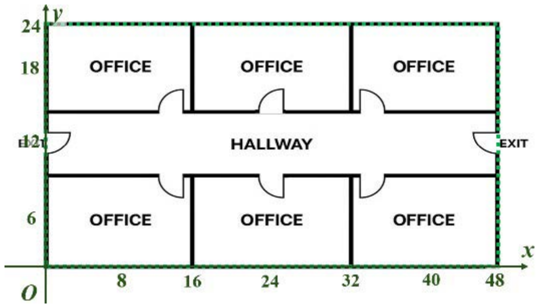

Figure 1 Layout of the single-story office building

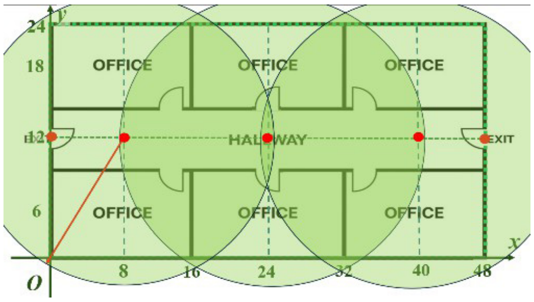

Figure 2 Inspection point distribution

1) Application Scenario

The test scenario is a single-story office building with 6 office rooms and a central hallway, as shown in Figure 1. Two responders start from the left and right exits respectively, traverse all inspection points to complete the full-area sweep, and are prohibited from passing through exits midway. In heavy smoke conditions, visibility drops sharply, requiring densified inspection points to eliminate blind spots.

2) Decision Variables

· $x_{ijk} \in \{0,1\}$: whether responder i moves from node j to node k

· $y_{iv} \in \{0,1\}$: whether responder i first visits node v

3) Objective Function

The objective minimizes the maximum sweep time of two responders:

$$\min \max_{i} swp_i \tag{1}$$

Total sweep time includes movement and inspection:

$$swp_i = \frac{1}{v_i}\sum_{j \neq k} x_{ijk} d_{jk} + \sum_{v} y_{iv} t_{iv} \tag{2}$$

Where t_{iv} is the inspection time of responder i at node v

4) Core Constraints

Full coverage:

$$\sum_{i=1}^{2} y_{ia} = 1, \forall a \in V \tag{3}$$

Path continuity:

$$\sum_{k} x_{ijk} = \sum_{k} x_{ikj}, \forall j \notin \{s_i, t_i\} \tag{4}$$

Exit constraint:

$$x_{ijk} = 0, j \in EXIT \setminus \{s_i\}, k \notin \{t_i\} \tag{5}$$

5) Solution Method

A greedy algorithm is used to solve the model efficiently. It iteratively assigns the nearest unvisited point to the responder with the shorter current time, balancing workload and path length with low complexity for real-time use. Inspection point distributions are shown in Figure 2.

C. Multi-Story Sweep: Bi-Level Optimization Model

A two-layer inner scheduling optimization + outer personnel configuration model is proposed for a three-story composite building (daycare/residential/office) to solve multi-personnel collaboration, cross-floor scheduling and optimal personnel quantity problems, as shown in Figure 3. The model fully considers floor-specific room/exit differences and the speed, efficiency and cost characteristics of five personnel types (firefighters, medical staff, security, teachers/caregivers, engineers), with the dual goals of minimizing comprehensive cost and balancing efficiency, cost and professionalism.

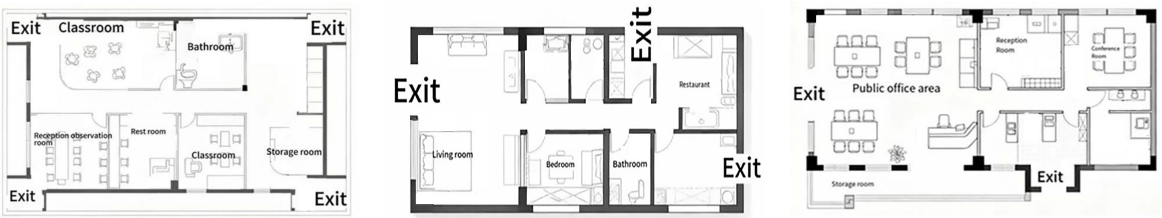

Figure 3 Three-Story Composite Building Layout

1) Application Scenario

1st floor (daycare, 7 rooms/4 exits), 2nd floor (residential, 7 rooms/3 exits), 3rd floor (office, 5 rooms/2 exits); cross-floor movement is constrained by stair travel time, with a floor-by-floor inspection sequence required.

2) Two-Layer Model Framework

Inner Model: Scheduling Optimization (Given Personnel Quantity)

Objective Function (minimize comprehensive cost):

$$min\left[T+\sum_{f=1}^{3}P_f+\sum_{p}c_p n_p T\right] \tag{6}$$

·T: Total building inspection completion time (determined by the 3rd floor finish time)

· $\sum_{f=1}^{3}P_f$: Coordination waiting penalty (for unbalanced floor workload)

· $\sum_p c_p n_p T$: Personnel time cost (reflecting professional time value differences)

Key Constraints

Room allocation: each room inspected by one person only

$$\sum_k y_i^k=1,\forall i \tag{7}$$

Path continuity: incoming/outgoing edges balance for non-start/end nodes

$$\sum_v x_{uv}^k=\sum_v x_{vu}^k \tag{8}$$

Cross-floor movement: next floor inspection starts only after current floor completion

$$t_{stairs,f+1}^k \geqslant C_f+t_{stairs} \tag{9}$$

Professional matching: tasks assigned based on personnel capability scores

$$y_i^k \leqslant skill_{p(k),i} \tag{10}$$

Time continuity: reflects speed differences of different personnel

$$t_v^k \geqslant t_u^k+s_u\cdot I_{room}(u)+\frac{d_{uv}}{v_{type(k)}} \tag{11}$$

Outer Model: Optimal Personnel Configuration Optimization

Objective Function (minimize total cost of inner optimization + fixed personnel cost):

$$\min_{n_p}\left[T^*(n_p)+\sum_p \alpha_p n_p\right] \tag{12}$$

· $T^*(n_p)$: Optimal comprehensive cost of the inner model for a given personnel configuration np

· $\sum_p \alpha_p n_p$: Fixed labor cost of personnel configuration (avoids oversized teams)

Personnel Quantity Constraints

Rescue guarantee: at least 1 firefighter and 1 security personnel for core rescue and layout guidance

$$n_{fir}\geqslant 1, n_{sec}\geqslant 1 \tag{13}$$

Vulnerable groups support: sufficient on-site guidance personnel for vulnerable groups

$$n_{sec}+n_{tea}\geqslant 2 \tag{14}$$

Quantity constraint: non-negative integer personnel with total number limits

$$n_p\in\mathbb{Z}^+,\sum_p n_p\in[n_{min},n_{max}] \tag{15}$$

3) Solution Method

· For the inner scheduling model: Given a fixed personnel configuration n_p, solve for the optimal task allocation, path planning and comprehensive cost $T^*(n_p)$ that satisfies all constraints.

· For the outer personnel configuration model: Calibrate all feasible personnel configuration combinations within the range $[n_{min},n_{max}]$, call the inner model to solve iteratively, and select the configuration with the minimum sum of "inner layer optimal cost + fixed cost".

· The iterative solution achieves the optimal balance between scheduling efficiency and personnel cost, with full consideration of professional matching and cross-floor coordination.

4. EXPERIMENTAL ANALYSIS

A. Single-Story Sweep Results

Two scenarios are tested: normal visibility and heavy smoke, as illustrated in Figure 4.

· In clear conditions, 21 inspection points are deployed to achieve full coverage. The greedy algorithm yields balanced cooperative paths with an optimal sweep time of 68 seconds.

· In heavy smoke, visibility drops from 8.5 m to 4.25 m; points are densified to 54 to eliminate blind spots. The sweep time rises by about 91% to 132 seconds, while full coverage is maintained.

Optimal cooperative paths are displayed in Figure 5. Results confirm that the OMTSPPFEAR model with the greedy algorithm generates safe, efficient, and adaptive sweep paths for both clear and smokefilled indoor environments.

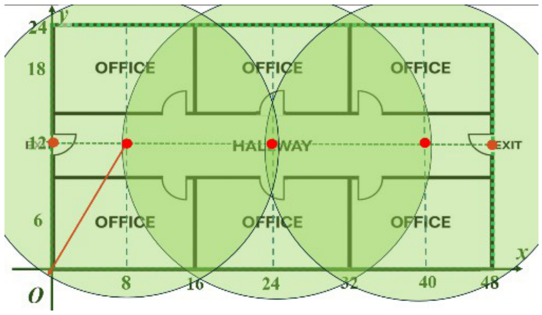

Figure 4 Inspection Point Deployment

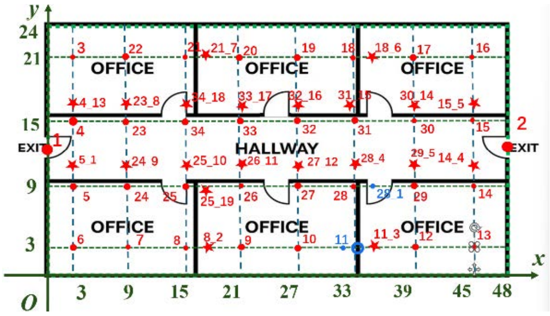

Figure 5 Optimal Sweep Paths

B. Multi-Story Scheduling Results

Three functional floors (daycare, residential, office) are tested.

· The inner model generates balanced cross-floor inspection sequences with strict professional matching and no path conflicts.

· The outer model yields a compact and effective personnel configuration, avoiding redundant staffing and reducing total cost.

· Under the optimal scheme, total inspection time is 212 seconds, with no coordination penalty and full coverage of all rooms.

Results confirm that the bi-level model efficiently coordinates multi-personnel cross-floor sweep tasks, improves overall efficiency, reduces cost, and provides reliable, practical schemes for multi-story composite buildings.

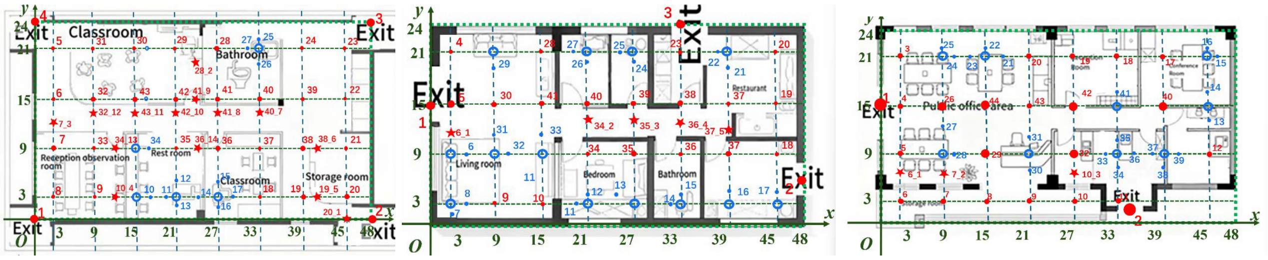

Figure 5 Optimal Sweep Paths of multi-story composite buildings

C. Model Advantages

1. Comprehensive constraint modeling for real emergency scenarios, integrating obstacle-forbidden edges, exit-only start/end rules, professional matching, and cross-floor coordination.

2. Hierarchical modeling adapting to single-story office buildings and multi-story composite buildings, covering both simple and complex structures with unified solution logic.

3. High interpretability and practical operability via intuitive greedy algorithms and bi-level iterative solutions, enabling direct real-world implementation.

4. Balanced optimization of efficiency, safety, and cost, minimizing sweep time (single-story) and comprehensive cost (multi-story).

D. Model Limitations

1. Increased computational complexity in large-scale scenarios; enumeration for multi-story personnel configuration and greedy algorithms for dense inspection points lead to longer solution times in super-large buildings.

2. Sensitivity to key parameters (personnel speed, inspection time, cost weights), requiring scenario-specific calibration.

5. CONCLUSION

This study addresses the critical problem of efficient, standardized safety inspections in complex building emergencies. By constructing a unified evacuation inspection system and proposing two targeted optimization models, we fill the gap in integrating path planning, multi-person collaboration, and multi-story scheduling under realistic constraints. The single-floor OMTSP-PFE-AR model with a greedy algorithm generates adaptive paths that maintain full coverage even under reduced visibility. The bi-level model for multi-story buildings realizes balanced cross-floor scheduling and optimal personnel configuration, reducing redundant resources while meeting rescue requirements. Experimental results verify the effectiveness, efficiency, and practicality of the framework. Future work will focus on improving algorithm scalability for super-large buildings, integrating real-time sensor data for dynamic adjustments, and extending the model to support complex emergency scenarios with time-varying risks and dynamic crowd distributions.

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