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Optimization-Based Planning of Emergency Building Sweeps Using a Multi-Agent Vehicle Routing Model

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Abstract. In emergencies, every second matters. First responders must ensure that no occupant is left behind while operating under conditions of limited visibility, increasing danger, and incomplete information. Well-designed evacuation plans reduce the risk to responders and improve the effectiveness of their efforts. In particular, efficient sweeping routes and techniques can be the difference between a safe evacuation and a preventable tragedy. To support emergency planning, we develop a rigorous model for evacuation sweeps those accounts for realistic building layouts and operational constraints. The sweep problem is formulated as a multi-agent routing and scheduling task, modeled as a Vehicle Routing Problem with service times and coordinated routes. Rooms are treated as mandatory service nodes, hallways and stairwells as weighted travel edges, and responders as routing agents. A mixed-integer optimization framework propagates travel and service times, while a makespan-minimization objective determines the shortest feasible complete-building sweep. The model is tested on a one-story office building and on multi-floor school and hospital layouts with varying room types, hazard patterns, and responder counts. Extensions incorporate factors such as hazard spread, communication delays, room priority, and occupant movement. Results show that the VRP-based approach is flexible, scalable, and effective for planning safe and efficient building sweeps, allowing responders to focus on execution rather than on-site planning.

Keywords: Evacuation planning; Vehicle Routing Problem; Emergency response; Multi-agent optimization; Building sweep.

1. Introduction

1.1. Background

Emergency evacuation planning is critical to building planners as safety must come first in the design of any building. In emergencies, it is crucial for first responders to use every second efficiently to ensure the safety of all occupants. Responders need to know the most efficient route to take when entering, sweeping, and leaving the building beforehand to ensure they can adequately evacuate the building when they arrive, as onsite delays waste critical time that could be the different between life and death. As modern architecture evolves to create ever-more unique building designs, of different shapes, sizes, and functions, it is often difficult to evaluate these new buildings on their safety in case of an emergency based on traditional frameworks that rely on the assumption of simple and conventional layouts. Rough estimates of building evacuation strategy time often result in miscalculations that prove fatal when emergencies occur. It is thus critical to develop a comprehensive model that not only checks each buildings layout to ensure that an evacuation can be completed in time during an emergency but also factors into account various adverse conditions that might delay the process to come to an accurate yet conservative estimate that checks back on the design of all buildings to make sure they are safe.

2. Assumptions

1. Building layout is known and does not change during evacuation: We assumed that when responders arrive at the building, they have full information of the building layout and would plan their route based on it; also, it is assumed that no collapse would happen to eliminate any rooms, or completely block all entrances of certain rooms.

Justification: First, there is enough time for the responders to gain information of the building before they arrive; second, in the overwhelming majority of emergencies, especially fires, collapse of building would not occur during evacuation. If happened, it often indicates that it is extremely dangerous to enter the building.

2. Layout is simplified into a graph: It is assumed that the layout could be simplified into a graph, such that nodes represent places such as rooms, entrances and staircases, and edges represent the path between two places. Length of the edge equals the length of the shortest feasible path between two places on the map, which does not directly pass through a third place. This path is determined by observation.

Justification: Before and during evacuation, responder could quickly find the optimal path from one room to another through observation. It is also acceptable to assume that all rooms are connected to the hallway, as that is the typical situation for most public buildings.

3. Only one source of time-dependent propagating hazards: We assumed that there is only one source of fire, or other spreading hazards in the building, and it would not cause any secondary incidents.

Justification: Most evacuation scenarios only include a single source of fire or other hazards. They typically start at a certain room, and then spread through hallways.

3. Variables

3.1. Variables

The following variables are used in modeling the static search and response process.

Environment

- G (V, E): Graph representation of the building layout, where nodes V represent individual spaces such as room, corridors or staircases, and edges E represent pathway between the spaces.
- A: Total area of a room, approximately measured by length × width (a × b).
- C: Room layout complexity, from 0 (completely visible from entrance) to 1 (highly complex).
- V: Visibility level affected by smoke or gas, from 0 (invisible) to 1 (completely clear).
- Et: Type of emergency, such as fire or gas leak.
- H: Hallway accessibility, from 0 (blocked or very difficult to move) to 1 (completely free). Too narrow hallways or obstacles would cause low value of H.

Occupant

- No: Number of occupants.
- Ty: Type of occupants, such as workers, patients, or children.
- Ac: Minimum communication ability of the occupants, determined by their English proficiency, hearing, and speaking ability. from 0 (cannot communicate verbally) to 1 (no communication barrier).

Responder

- Nr: Number of responders.
- pr: level of skill or experience of the responders, from 0 (no experience) to 1 (ideal training). This would affect both searching and movement speed.

Redundancy

- Q: Double-check condition (1 if required, 0 otherwise).
- cr: Communication reliability between responders.

Safety Rules

- Rs: Safety rule coefficient, representing how strict the search protocol is.
- Ts: Total search time limit for all rooms.
- p safe: Confidence level that no occupants remain in a room.

4. Model Overview

4.1. Modified Sweep Routing Problem Overview

The problem requires responders to sweep all the rooms in a complex floor plan and rescue everyone in the shortest possible time. Such an optimization requires optimizing routes between nodes, so we consider it with the same approach as the vehicle routing problem (VRP).

VRP is a classic problem in graph theory that addresses the optimal routes for cars to balance travel time, cost and resources. The basic objective of VRP is to minimize the total route cost, as it originally considers the vehicle routing for last-mile deliveries.

To apply the VRP method to this problem, rooms, stairwells, corridor intersections, or any independent space that needs to be searched can be considered as vertices; passageways between rooms, corridors, and staircases can be considered as edges. Each edge is assigned a weight, which is reflected by the passage time, risk level, etc. The depot in the VRP problem is the starting position of the responder or the entrance point into the building in this problem.

In essence, the idea of VRP will be used in the model for this problem to find the fastest sweeping method by optimizing the route that is used to sweep any building, with specific factors of emergency and building circumstances turned into weights within the VRP problem. This method allows the problem to be abstracted down into a simple optimization method that encompasses various complex factors within a weight for each edge for calculations. It also allows building plans to be turned into graphs with nodes and edges so all buildings layouts are drawn in the same general way in a graphical illustration. The specific application of VRP method onto this problem will be called the The Modified Sweep Routing Model.

4.2. Time based cost function

To evaluate total sweeping efficiency, we define two kind of time-related costs: (1) node service time, which represents time spent on searching each visited room, and (2) edge movement time, which represents time required to travel between rooms. Together, these values define the total time required to sweep the building, which serves both as the model output and part of the objective that need to be minimized in the Modified Sweep Routing Model. All time are measured in seconds.

4.2.1. Room Service Time

Each room i requires a service time determined by either physical searching or communication-based response confirmation. Since responders may confirm room clearance through verbal communication prior to completing a full search, the effective room service time is defined as:

$$T_i^s = \min(T_{search,i}, T_{respond,i})$$

(a) Searching Time

$$T_{search,i} = \frac{A_i}{10} * (C_i^2 + 1) * \frac{1}{V_i} * (1.5 - P_r)$$

where

• Ai = area of room i (m2). We assumed that when Ci = 0, Vi = 1, Pr = 0.5, a responder could visually check 10 m2 of area.

• Ci = layout complexity factor (0–1), squared to model non-linear impact on searching time. Larger values of Ci evidently increase the required time due to obstructed view of responders.

• Vi = visibility factor (0–1), where lower visibility slows searching. When Vi approaches 0, searching time would approach infinity as it is impossible to see at all. This leaves verbal confirmation as the only possible method.

• Pr = responder proficiency (0–1). We assumed that a perfectly trained firefighter (Pr = 1) could search a room 3 times faster than an individual with no experience at all (Pr = 0).

(b) Response Confirmation Time

$$T_{respond,i} = 5\sqrt{N_{o,i}} * (1.5 - P_r) * \frac{1}{\sqrt{A_{c,i}}}$$

where

• No,i = number of occupants inside room i. More occupants cause increased time for communication, but time would not increase linearly as communication happens between the responder and multiple occupants. It is assumed that when No,i = 1, Pr = 0.5, Ac,i = 1, communication is completed in 5 seconds.

• Ac,i = communication ability factor of occupants (0–1). Ac,i = 0 indicate that at least one occupant cannot verbally respond at all because of communication barriers, making it necessary to physically search the whole room.

4.2.2. Movement Time Between Nodes

Traversal between two nodes i and j is affected by distance, visibility, hallway mobility, and responder proficiency. The movement time is defined as:

$$T_{ij}^M = \frac{r_{ij}}{4} * (3 - P_r) * (1.5 - V) * (1.5 - H)$$

where

• rij = geometric distance between nodes i and j. Transformed as weight of edges on the graph. It is assumed that when pr = 0.5, V = 1, H = 1, which models an ideal environmental condition, the responder could move with a speed of 2.5 m/s.

• V = visibility factor in shared pathway. It is assumed that worst visibility(V = 0) reduce responders' movement speed to one third of the speed when V = 1.

• H = hallway mobility factor (0–1), representing obstacles and difficulty. Worst condition would largely reduce movement speed to one third, as the responder might need to first clear the barriers before passing.

4.2.3. Edge Cost Definition for VRP

To integrate both movement and service components, the final edge cost used in the routing model is defined as:

$$C_{ij} = T_{m,ij} + T_{s,j}$$

This represents the total time required to move from node i to node j and then complete the room clearance operation.

5. Model - Problem 2

5.1. VRP with Penalty Costs for Optional Nodes

In the classical Vehicle Routing Problem (VRP), every non-depot node must be visited exactly once by one of the vehicles. However, many practical scenarios require some nodes to be optional: the route may visit them, but it is also allowed to skip them at a certain penalty cost.

This extended formulation is known as a VRP with penalties (or "Prize-Collecting VRP").
Let xi be a binary variable indicating whether node i is visited. Let c(route) be the usual routing cost. Then the objective becomes

$$\min c(route) + \sum(1 - x_i)p_i$$

where O is the set of optional nodes. Setting Pi = 0 makes node i completely optional: the solver will only visit it if it is needed to reach mandatory nodes or if it shortens the route.

5.2. Our Modeling Requirements

In the fire-evacuation inspection problem studied here, the building consists of two entrances/exits (denoted L and R) and six rooms that must be searched. We have the following requirements:

- Some nodes must be visited:

M = {TL, TM, TR, BL, BM, BR},

since each room must be searched exactly once.

- Some nodes are optional: the physical entrances/exits L and R themselves need not be "visited" in the VRP sense; they only serve as possible access points into the building.

• All firefighters start from a virtual depot S outside the building and must eventually return to S.

- Importantly, a firefighter may enter the building through either L or R and may leave through either of them. Hence a feasible route may look like

S → L → (rooms) → R → S,

or the symmetric alternative. Therefore, L and R must be allowed to serve as either entrance or exit.

- Rooms are located behind the entrances; thus, the model must forbid a vehicle from going directly S → room or room → S without passing through an entrance/exit.

5.3. Graph Transformation for Modeling Optional Gateways

Standard VRP solvers such as the OR-Tools Routing Solver do not allow a node to be visited multiple times, nor do they permit specifying that a node must be passed in transit without being "visited". To correctly represent that the building entrances L and R are optional and that vehicles may enter through them and separately leave through them, we perform the following transformation.

1. Introduce a virtual super-depot S. All firefighters start at S and must return to S at the end of their route. Node S is not a physical location; it merely represents the staging area outside the building.

$$\text{starts}(k) = S, \qquad \text{ends}(k) = S, \qquad \forall k.$$

2. Split each physical gateway into an "entry" and "exit" node. The physical entrances L and R are split into two logical nodes each:

$$\{\text{Lin}, \text{Lout}, \text{Rin}, \text{Rout}\}.$$

Interpretation:

- Lin: the only way to enter the building through L.
- Lout: the only way to leave the building through L.
- similarly for Rin and R out.

This ensures that entering and leaving are treated as two distinct actions, each allowed at most once per vehicle, in accordance with the Routing Model constraints.

3. Optional gateways via penalty-zero disjunctions. Each of the gateway nodes

$O = \{\text{Lin}, \text{Lout}, \text{Rin}, \text{Rout}\}$

is declared optional by attaching a zero-penalty disjunction:

$$\text{vehicle may skip Lin} \qquad \Longleftrightarrow \qquad \text{penalty} = 0.$$

Hence the solver is free to choose any of the four nodes as the entrance/exit points, including the possibility that one or more of them remain unused.

4. Mandatory service nodes. All room nodes form the set M of mandatory nodes:

$$M = \{TL, TM, TR, BL, BM, BR\}.$$

These nodes are not given disjunctions and therefore must be visited exactly once by the routes.

5.4. Effect of the Transformation

After the transformation, a feasible route of a firefighter must have the form

$$S \rightarrow (\text{one of Lin, Rin}) \rightarrow (\text{sequence of mandatory rooms}) \rightarrow (\text{one of Lout, Rout}) \rightarrow S,$$

but the solver is allowed to choose which entrance and exit to use, and different vehicles may enter and leave through different gateways.

This modeling technique simultaneously satisfies:

Such a graph transformation is fully compatible with the OR-Tools Routing Model, respects its "each node visited at most once" constraint, and encodes the physical building-access logic exactly.

5.5. Office Sweeping Results

The model found that the optimal route for the firefighters to sweep the office building are as follows:

Firefighter 1: S → Lin0 → Lout0 → TL → TM → TR → Rin0 → Rout0 → S Route time = 390 s

Firefighter 2: S- > Rin1 - > Rout1 - > BR- > BM- > BL- > Lin1 - > Lout1 - > S Route time = 390 s

Total time (max route time among firefighters) = 390 s

As such, the sweep model developed found that the with optimized routes deploying two firefighters, it takes 390 seconds to fully sweep and evacuate the office building in the base case.

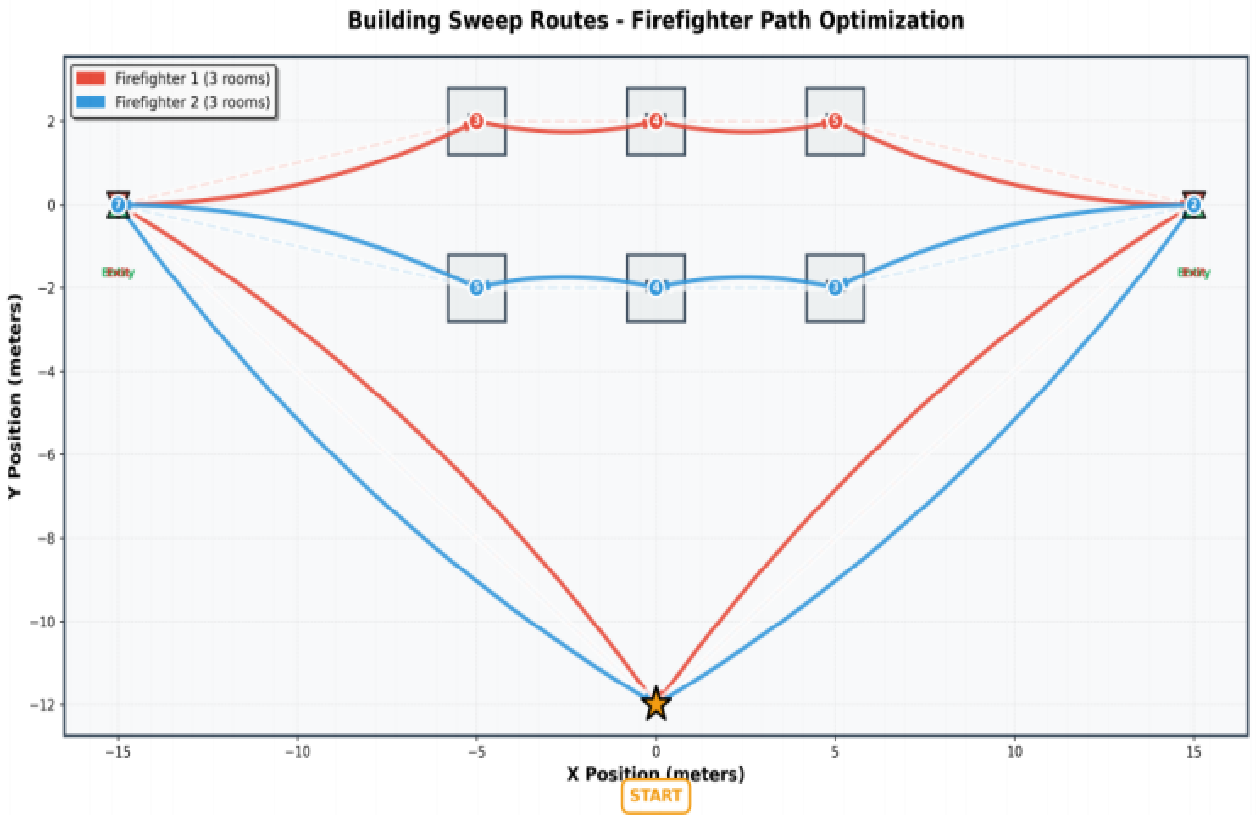

Figure 1. Office Route

6. Application

6.1. Additional Building Layout

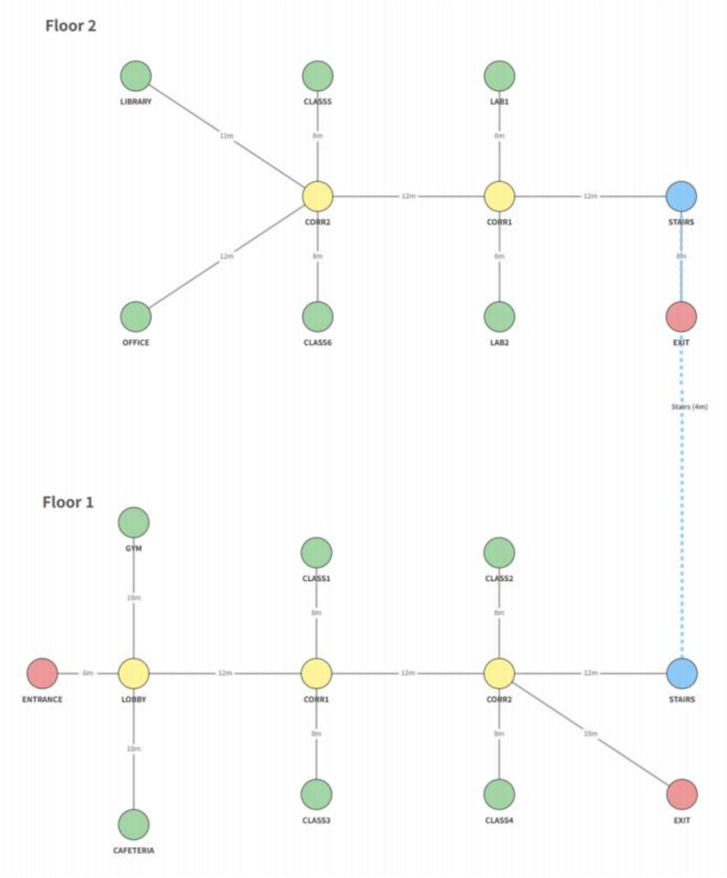

Figure 2. School Layout

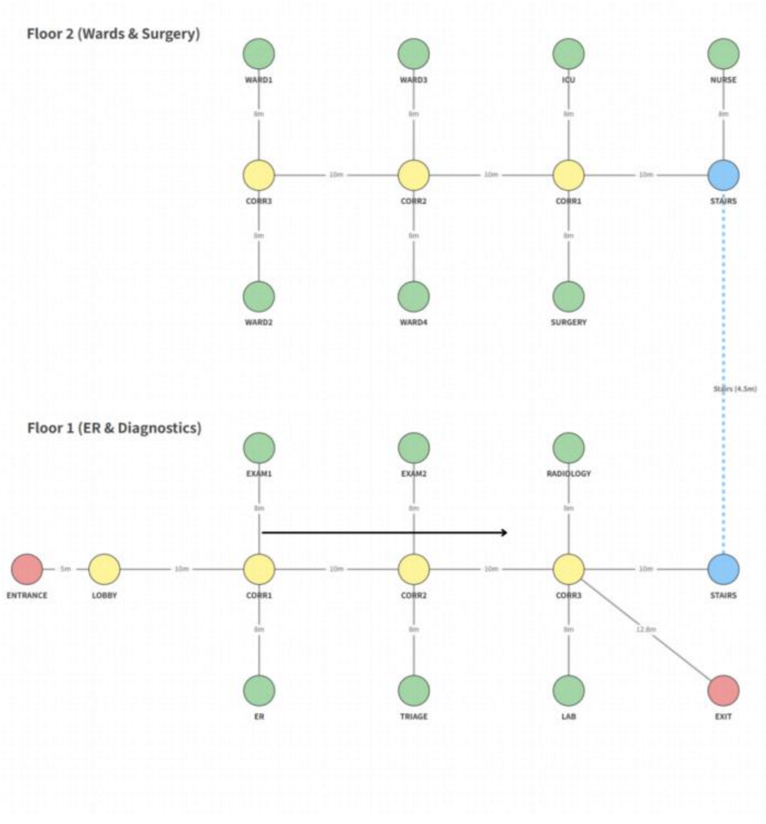

Figure 3. Hospital Layout

The school and the hospital share similar layout. They are both 2-floor buildings with hallways that connects all rooms, and they only have 1 staircase at the side of the building. Variables are assigned to individual rooms based on real-life scenario.

6.2. Result for School Layout

In the base scenario of considering 2 firefighters, the optimal route for the firefighters to take in the building is as follows (corridors are omitted):

Firefighter 1: S → S1EXIT → S1STAIRS R1 → S2LAB1 → S2LAB2 → S2LIBRARY → S2CLASS5 → S2OFFICE → S2CLASS6 → S2STAIRS R0 → S2EXIT → S

Route time: 483 s

Firefighter 2: S → S1ENTRANCE → S1GYM → S1CAFETERIA → S1CLASS1 → S1CLASS3 → S1CLASS2 → S1CLASS4 → S1EXIT → S

Route time = 483s

Total time (max route time among firefighters) = 483s

As the number of firefighters deployed varies, with resulting optimal times can be graphed in the chart below.

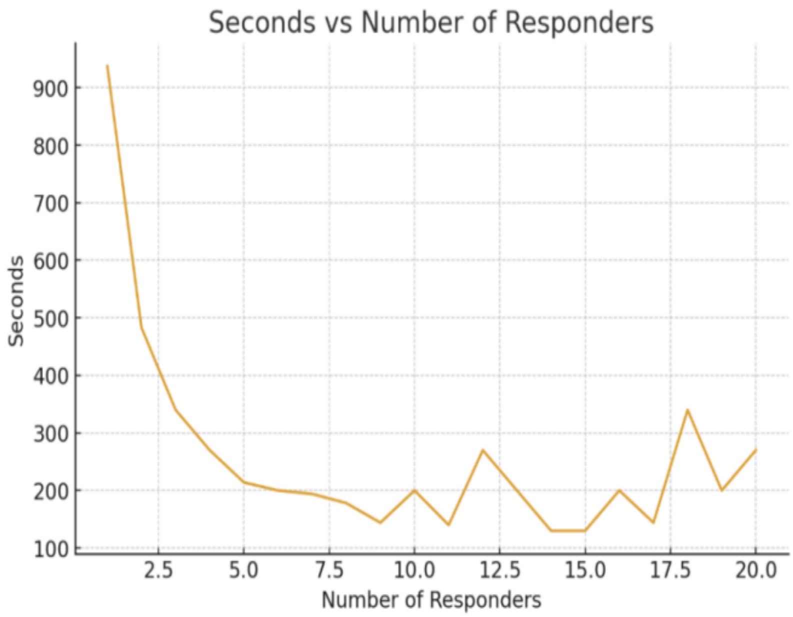

Figure 4. School Timings

The optimal number of responders to minimize time is 14 to 15 responders as the time taken to sweep is minimized at 130 seconds. However, it is reasonable to determine 5 as the most efficient number of responders, as any further increase in N have little positive effect on time. The cause of this might be that no matter how many responders there are, they always have to reach the furthest room from entries.

6.3. Result for Hospital Layout

In the base scenario of considering 2 firefighters, the optimal route for the firefighters to take in the building is as follows (corridors are omitted):

Firefighter 1: S → S1Exit → S1STAIRS R1 → S2ICU → S2SURGERY → S2WARD3 → S2WARD4 → S2WARD1 → S2WARD2 → S2STAIRS R0 → S1EXIT → S

Route time = 521s

Firefighter 2: S → S1ENTRANCE → S1EXAM1 → S1ER → S1EXAM2 → S1TRIAGE → S1RADIOLOGY → S1LAB → S1STAIRS R1 → S2NURSE → S2STAIRS R0 → S1EXIT → S

Route time = 55s

Total time (max route time among firefighters) = 555s

As the number of firefighters deployed varies, with resulting optimal times can be graphed in the chart below.

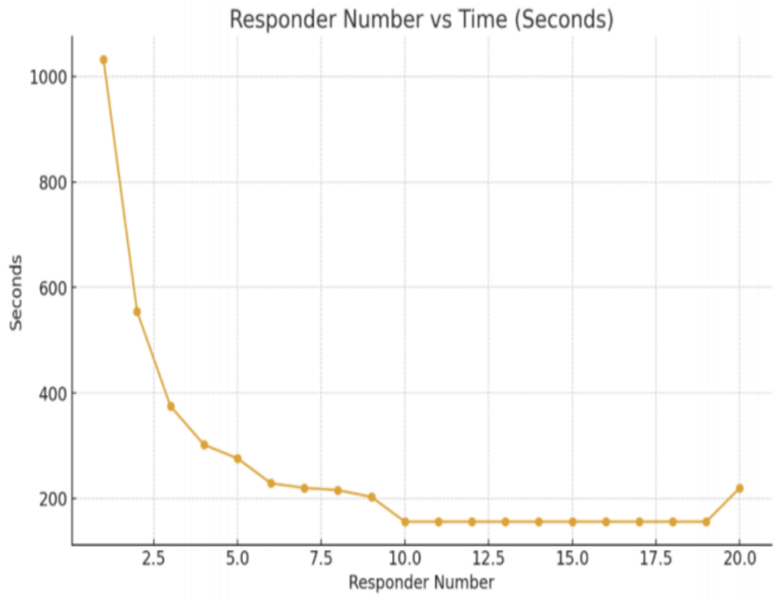

Figure 5. Hospital Timing

The optimal number of responders is any number of responders from 10 to 19 as it minimizes the time taken to sweep at 156 seconds. Similarly, 6 responders could be considered the most efficient number, although there is a notable time difference from 9 to 10 responders. The constant time again demonstrates that time for movement makes up the majority of overall sweeping time in this case.

7. Conclusion

This study addresses the critical challenge of emergency evacuation by optimizing the balance between speed and safety. We developed a comprehensive mathematical modeling and optimization framework to tackle this problem. At its core, the solution integrates an enhanced Selective Vehicle Routing Problem with a Team Orienteering framework, effectively minimizing total evacuation time without compromising safety.

A key methodological contribution lies in representing building layouts as weighted network graphs derived from room-path structures. This simplification allows the model to combine the route optimization strengths of vehicle routing problems with the mandatory point-visitation requirements of team orienteering. The resulting framework can handle complex spatial constraints while ensuring complete coverage during evacuation operations.

To enhance practical applicability, we introduced a streamlined parameter system that converts diverse real-world factors into normalized values within a [0,1] range. This design provides an intuitive interface for emergency commanders, who can utilize the model without extensive training in optimization theory. Testing across multiple building types—including offices, schools, and hospitals—demonstrates the model's adaptability and consistent performance. Sensitivity analyses produced several valuable insights: for instance, a training proficiency threshold of approximately 0.7 for response personnel was identified as optimal; distributed deployment strategies increased efficiency by about 22% in multi- story buildings; and deteriorating conditions were found to potentially extend evacuation times for individual rooms by up to 23%. These findings provide an evidence-based foundation for strategic resource allocation and tactical planning.

While the framework delivers both theoretical and practical contributions, certain limitations remain. Computational performance may be challenging in very large complexes, normalized parameter still requires careful judgment, and dynamic occupant behavior is currently simplified. These areas point to opportunities for future work, such as developing advanced heuristic algorithms, creating standardized parameter databases, and integrating more sophisticated behavioral models.

In summary, this research presents a scientifically grounded decision-support tool for emergency evacuation planning. The combination of theoretical innovation and practical applicability provides a foundation for enhancing building safety and improving operational response effectiveness.

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