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Research Article

How to Escape from Fire: Insights and Strategies Inspired by an Urban High-Rise Outbreak

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Abstract

The recent high-rise fire at Wang Fuk Court in Hong Kong is a stark reminder of how quickly a familiar space can become deadly. Within minutes, breathable air can degrade, visibility can collapse, and seemingly safe routes can vanish. Drawing on observational accounts, fire-safety research, and simple, transparent modeling, this paper examines how occupants and responders can improve survival in sudden indoor fire emergencies. We provide a structured account of how interior conditions deteriorate as a fire develops, identify key human factors that shape behavior under stress, and translate these insights into zone-based evacuation guidance and responder sweep strategies. We also introduce interpretable quantitative models for zone-level smoke and toxicity, hazard indices, and evacuation-time estimation, and demonstrate their use through simulation-style experiments in a multi-floor template building that compare naive and zone-aware approaches. The goal is to offer practical, actionable guidance grounded in real-world constraints, rather than relying solely on idealized fluid-dynamics formulations.

Keywords: Fire Safety; Evacuation; Emergency Response; Building Layout; Zone-Based Strategies; Routing.

Introduction

Urban fire emergencies are among the most unpredictable and destructive hazards in dense cities. Within seconds, a calm interior environment can devolve into darkness, heat, toxic fumes, and disorientation. Recent high-rise fires have vividly illustrated this reality: residents trapped in hallways, responders struggling through zero-visibility corridors, and casualties caused not only by flames but also by smoke inhalation, toxic gases, and confusion [1,2].

These events sharpen a critical question: *How can occupants escape swiftly and safely when their building becomes a hazard zone?* Fire science offers detailed models of ignition, fire growth, and smoke movement [1,3], and there is a rich body of work on human behavior in fire and evacuation modeling [3-5]. However, the human-level reality of movement, decision-making, and survival strategies under stress often receives less practical emphasis in everyday safety communication and building-level planning.

This paper attempts to narrow that gap. We use an urban high-rise incident as a motivating scenario and synthesize lessons from fire dynamics, human behavior research, and evacuation modeling into a coherent framework of escape and sweep strategies. We deliberately adopt simple, interpretable models that can be communicated to building managers, safety officers, and responders, rather than highly detailed CFD [6] or agent-based tools that require specialist expertise.

Contributions. Concretely, this work makes three contributions:

1. **Qualitative framework linking hazard and behavior.** We provide a structured description of how interior environments deteriorate during a fire (smoke, CO, temperature, visibility)

and how this interacts with human perception, decision-making, and congestion.

2. **Simple quantitative models and graph-based formulation.** We introduce compact equations for zone-level hazard and hazard-dependent walking speed, and formulate occupant routing and responder sweeps as shortest-path and TSP-style problems on a graph representation of the building.
3. **Simulation-style comparison of strategies.** Using a three-floor template building, we compare a naive "single familiar exit" strategy against a zone-based, multi-exit strategy, showing how the latter can reduce evacuation time, exposure to critical hazard, and responder sweep distance.
4. **Visual analytics templates for planning and drills.** We propose concrete hazard, flow, and time–hazard visualizations that make zoning and rerouting rules easy to train and execute.

Figure 2 illustrates the central idea of partitioning a floor into zones with distinct primary and secondary exits, thereby reducing convergence on a single, potentially compromised stairwell.

Related Work

This section briefly reviews relevant literature on fire dynamics, human behavior in fire, and evacuation modeling, situating our contribution with respect to existing work.

A. Fire Dynamics and Toxic Hazards

Classical fire science describes how ignition, heat release rate, ventilation, and compartment geometry interact to pro- duce rapidly changing interior conditions [1]. The SFPE Handbook summarizes the evolution of temperature, smoke layers, and tenability limits for typical residential and office compartments. Purser provides widely used models and criteria for toxicity and incapacitation due to combustion products, emphasizing the dominant role of carbon monoxide (CO), irritant gases, and oxygen depletion [3].

Our zone-level hazard model is deliberately simpler than modern CFD or zone fire models, but conceptually aligned with these standard tenability criteria - we track CO, smoke (optical density), and temperature, and combine them into a dimensionless hazard index.

B. Human Behavior in Fire

Human responses to alarms are shaped by pre-movement delays, risk perception, social influence, and access to in- formation [2]. Kuligowski's review in the SFPE Handbook [7,8] synthesizes evidence that many occupants initially search for confirmation or instructions rather than immediately evacuating. Fahy and Proulx compiled empirical data on delays before starting to evacuate and walking speeds under different conditions [9]. These works show that

- delays of tens of seconds to a few minutes are common;
- walking speed is heavily influenced by smoke, crowding, and familiarity;
- misconceptions about "panic" often obscure the real issues of information and coordination.

We incorporate these insights qualitatively in our discussion of decision-making [10] and quantitatively via a hazard- dependent walking-speed function.

C. Evacuation Modeling and Routing

Evacuation modeling has evolved from early hand calculations to sophisticated computational tools [4,5]. Gwynne et al. review methodologies used in simulating evacuation from the built environment, including network-based, cellular automata, and continuous models [5]. Ronchi and Nilsson dis- cuss the role of evacuation modeling in fire safety engineering and its limitations, calling for better representation of human behavior and decision making [4].

Routing problems in evacuation have been studied using network flow and optimization tools. Cova and Johnson pro- posed a lane-based network flow model [11] for evacuation routing under time pressure [12]. Chen and Feng presented a fast flow control algorithm for real time evacuation in large indoor areas [13]. These models often assume an external control system that reallocates flows dynamically.

Instead of proposing yet another detailed algorithm, we show how a simple graph-based view and TSP-style reasoning can be used to design *human-implementable* zoning and sweep rules.

D. Positioning This Work

In contrast to full CFD models that resolve flame and smoke flow in great detail, and high-fidelity agent-based simulations with complex behavioral rules, we focus on low-order, interpretable models that

a) capture the direction and relative timing of hazard escalation;
b) allow simple, graph-based reasoning about routes and sweeps;
c) are easy to explain to non-specialists and incorporate into drills and signage.

The simulation-style results are illustrative rather than predictive, but they support concrete, actionable design recommendations.

Figure 1 summarizes the end-to-end logic of the paper - we start from how hazards evolve in zones, translate that into hazard-aware movement costs on a building graph, compare two human implementable strategies via simulation style experiments, and finally present drill friendly visual templates that connect results to actionable rules.

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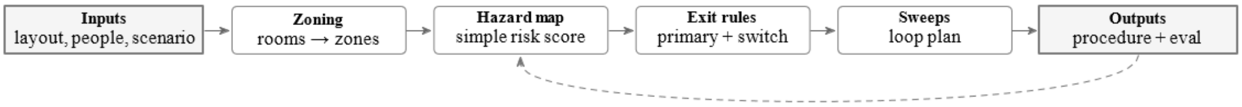

Figure 1: Compact overview of our method (two-line boxes: function then how). Dashed arrow indicates iterative refinement using simulation/ drills.

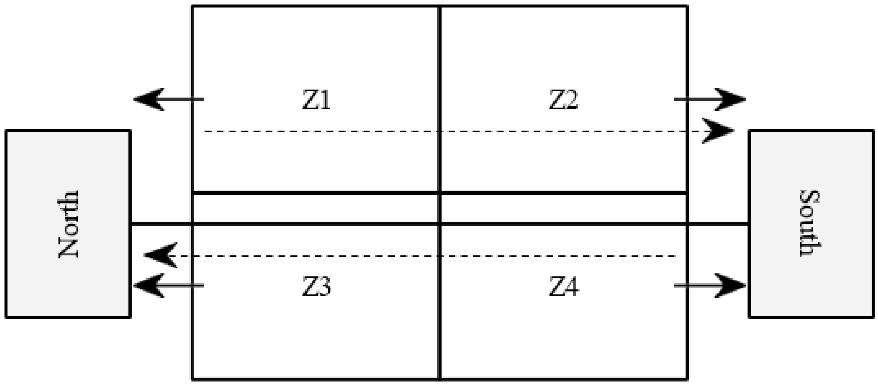

Figure 2: Illustrative floor plan segmented into four evacuation zones (Z1–Z4), each with a primary (solid arrows) and secondary (dashed) exit.

Dynamics of Fire-Induced Danger

We view the building as partitioned into N well-mixed zones (rooms, corridor segments, or stairwells). For each zone i ∈ {1, . . . , N } we track

- $C_i(t)$: CO concentration (ppm),
- $S_i(t)$: smoke density (e.g., optical density, 1/m),
- $T_i(t)$: air temperature (K),
- $V_i(t)$: derived visibility.

Let N (i) denote the set of zones adjacent to zone i (e.g., connected by a door opening, corridor segment, or vertical shaft), which governs inter-zone exchange.

A. CO, Smoke, and Temperature

Rather than using a high-fidelity CFD model, we adopt a simple *zone-balance* view: each quantity changes due to (i) local source terms (fire or heat), (ii) removal (ventilation/leakage), and (iii) exchange with adjacent zones.

A representative example is the CO balance:

$$\frac{dC_i(t)}{dt} = a_i - b_i C_i(t) + \sum_{i\in N(i)} k_{ij} C_j(t) - C_i(t)), \qquad 1$$

where a_i is the local emission (nonzero near the fire), b_i is a removal rate, and k_{ij} captures inter-zone exchange.

Smoke and temperature can be modeled using the same neighbor-coupled structure, each with its own source, removal, and coupling parameters. For brevity, we omit the full equations and note that the same neighbor-sum term applies. Smoke includes production near the fire, removal via ventilation and deposition, and exchange through openings; **temperature** includes heat input near the fire and coupling to adjacent zones.

These low-order dynamics are not intended to predict exact concentrations, but to capture the *relative escalation* of hazard across zones in a way that supports routing and planning.

B. Visibility Model

Visibility Vi(t) is coupled to smoke density Si(t) via an empirical relation commonly used in fire engineering [3],

$$V_i(t) = V_{\max}\exp(-kS_i(t)), \qquad 2$$

where $V_{\max}$ is clear-air visibility and $\kappa > 0$ is a material dependent coefficient.

Figure 3 illustrates the exponential link in Eq. (2): as smoke density S increases, visibility V drops quickly. The steep early decline means even moderate smoke can reduce sight distance by several meters, affecting wayfinding and slowing movement well before other hazards become critical. The parameter κ controls how fast this decay happens (larger κ

→ faster visibility loss).

C. Hazard Index for Each Zone

To drive routing decisions we combine CO, temperature, and visibility into a single dimensionless hazard index Hi(t),

$$H_i(t) = w_1 \frac{C_i(t)}{C_{crit}} + w_2 \frac{T_i(t) - T_o}{T_{crit} - T_o} + w_3 (1 - \frac{V_i(t)}{V_o}), \quad 3$$

where C_{crit} and T_{crit} are critical thresholds, T0 is ambient temperature, V0 is a reference visibility (e.g., 10 m), and w1 + w2 + w3 = 1.

The goal is not to claim a universal "true" danger score, but to obtain an interpretable planning metric that (i) increases as conditions worsen, (ii) allows comparisons across zones intuition: high toxicity, high heat, or low visibility should each push a route toward avoidance. We therefore normalize each component by a reference or critical level and take a convex combination, so $H_i(t)$ can be read as a weighted "fraction of criticality" aggregated across the main impairments that matter for evacuation and sweep planning. We interpret $H_i(t)$ using three coarse bands:

$$H_i(t) \begin{cases} , < 0.5, safe, \\ [0.5, 1], m\arg inal, \\ , \geq 1, critical. \end{cases} \quad 4$$

For the numerical experiments we use the representative parameters in Table I.

D. Discrete-Time Update Used in Simulation

Table 1: Representative Parameter Values for Zone-Level Hazard Modeling.

Parameter	Meaning	Value
C_{crit}	CO critical level	1200 ppm
T_{crit}	Critical temp.	373 K (100 ∘ C)
T_0	Ambient temp.	293 K (20 ∘ C)
V_0	Reference visibility	10 m
V_{max}	Clear-air visibility	20 m
w_1, w_2, w_3	Hazard weights	0.4, 0.3, 0.3
κ	Smoke-visibility coeff.	0.6

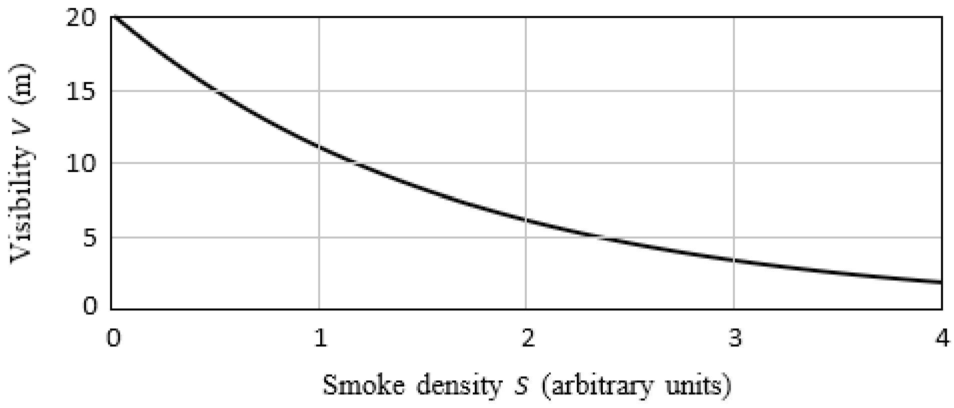

Figure 3: Illustrative relation between smoke density S and visibility V using $V = 20e^{-0.6S}$.

In the simulation-style experiments, we update the hazard index directly using a simple neighbor-coupled rule,

$$H_i^{t+\Delta t} = H_i^t + \alpha_i \Delta t + \sum_{j \in N(i)} \beta_{ij} (H_i^t - H_i^t) - \gamma_i u_i^t \Delta t, \quad 5$$

where αi is the local growth rate (largest near the source), β_{ij} controls propagation across openings, and the last term captures optional mitigation actions u_i^t (e.g., closing doors or boosting ventilation). This compact form preserves the qualitative behavior needed for routing hazards rise fastest near the source, spread along connectivity, and can be slowed by basic interventions.

Evacuation Time, Graph Modeling, and Strategy

We now model how evolving hazard reshapes *movement* and *decisions* - it slows occupants inside smoky/hot/toxic zones, changes which routes remain tenable over time, and turns "shortest path" into a time-dependent trade-off between distance and risk. We then show that both zoning (assigning areas to exits/teams) and responder sweeps (systematically checking rooms) can be expressed cleanly on a graph representation of the floor plan, which provides a unified way to compare strategies and design efficient, interpretable plans.

A. *Speed as a Function of Hazard*

Walking speed is known to decrease with smoke, heat, and crowding [9,14]. We model walking speed vi in zone i as a decreasing exponential function of hazard

$$V_i(H_i) = V_o \exp(-kH_i), \qquad (6)$$

where v0 is nominal speed (e.g., 1.2 m/s) and k > 0 reflects slowdown due to poor visibility, heat, and stress.

Figure 4 illustrates that as *H* increases, speed drops quickly at first and then continues to taper off. This reflects the practical observation that even moderate smoke/heat can trigger hesitation and slower movement, so time costs can rise sharply in higher-hazard zones.

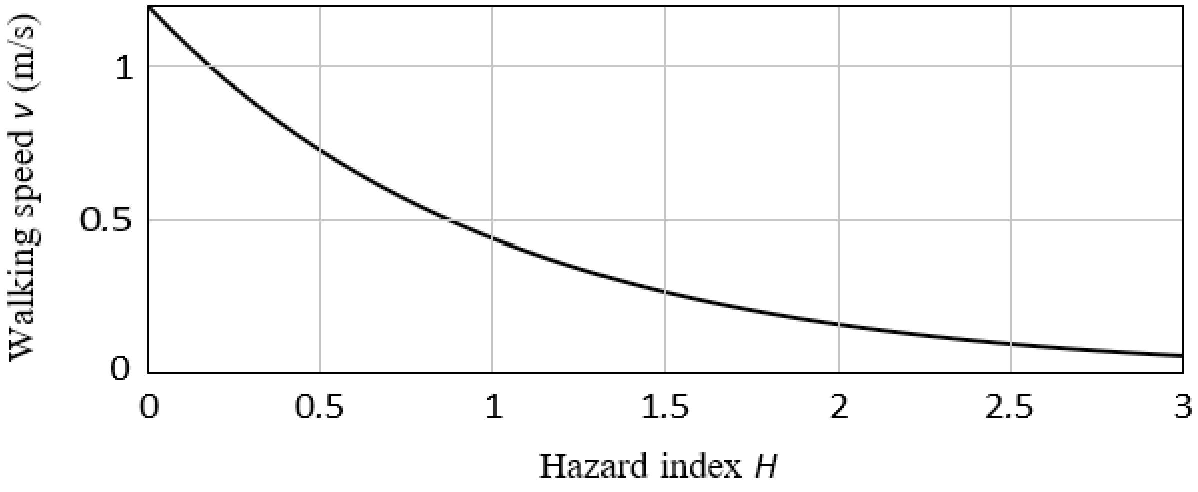

Figure 4: Walking speed v(H) = 1.2e^{-H}: hazard growth rapidly reduces effective speed.

B. *Route Evacuation Time*

Let a candidate evacuation route r be a sequence of zones r = (i_1, i_2, . . . , i_K), with distances $d_{i\ell i\ell+1}$ between adjacent zones. If an occupant enters zone iℓ at time tℓ, the travel time through that segment is approximated by

$$\Delta t_\ell \approx \frac{d_{i\ell i\ell+1}}{V_{i\ell}(H_{i\ell}(t_\ell))}, \quad 7$$

The total evacuation time along route r is then

$$\tau(r) = \sum_{\ell=1}^{k-1} \frac{d_{i\ell i\ell+1}}{V_{i_\ell}(H_{i\ell}(t_\ell))}, \quad 8$$

If at any step $H_{i\ell}$ (t_ℓ) exceeds a hard threshold H_{max} (e.g., 1.2), we treat *τ (r)* as effectively infinite, meaning the route fails tenability criteria.

Figure 5 compares two routes by showing how their encountered hazard increases over time. Route A crosses into higher hazard sooner (short but close to the fire), while Route B rises more slowly (longer but cleaner). The figure highlights the key trade-off-the path that is geometrically shorter can become less attractive once hazard escalates.

C. *Sweep Strategy as an Optimization Problem*

We can view the assignment of zones to exits and sweep teams as a planning problem: *each zone selects a primary exit, and the goal is to reduce overall evacuation time while avoiding routes that enter critical hazard too early* Figure 6. In practice, this can be implemented with simple rules (e.g., assign each zone to the currently "best" exit under the latest hazard map) and then refined with capacity checks (e.g., avoid overloading a stairwell).

D. *Graph-Based Search and TSP-Inspired Sweep Planning*

The zone layout can be represented as a graph

$$G = (V, E),$$

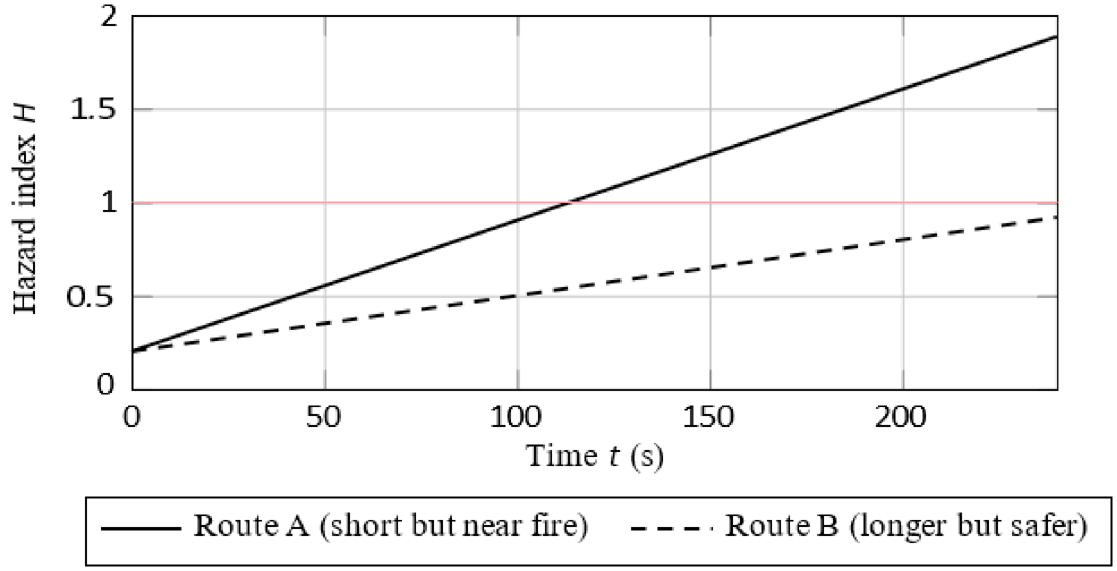

Figure 5: Illustrative hazard growth along two evacuation routes. A shorter path (Route A) encounters higher hazard earlier than a slightly longer alternative (Route B).

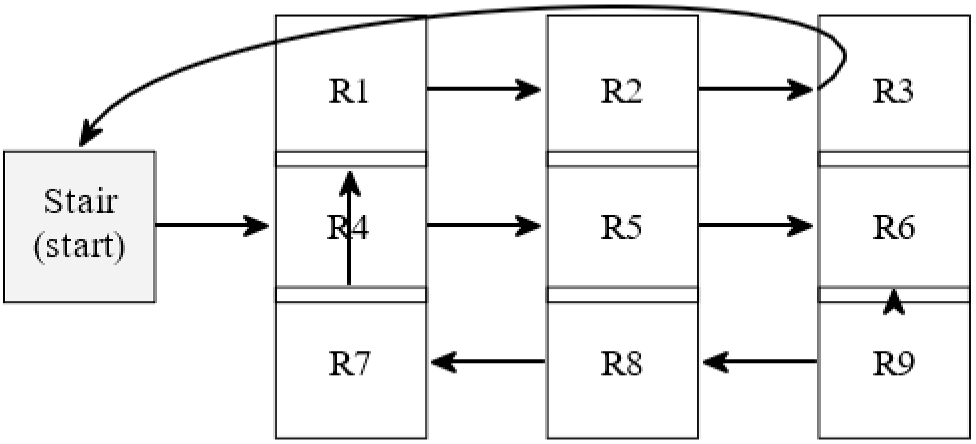

Figure 6: Illustrative TSP-style responder sweep: a single loop (solid arrows) visits each room once and returns to the stair, reducing overlap and missed areas within a zone.

where nodes are rooms/corridor segments/stairwells and edges indicate direct passable connections. Hazard affects movement by inflating the effective travel time of edges moving through a more hazardous node becomes slower, so the same geometric distance can have a larger time cost during a fire.

Occupant routing as shortest-path search: Occupant routing can be interpreted as a shortest-path problem on the graph - starting from a node s, choose a path to an exit that minimizes *time*, where time depends on both distance and the current hazard map. In clear conditions, the shortest path tends to match the geometrically shortest route. As hazard evolves, edges passing through high-hazard areas become “expensive,” so the preferred route can shift to a cleaner detour. A simple practical approach is to recompute a best route whenever new hazard estimates arrive, similar to dynamic routing in evacuation networks [12,13].

Responder sweeps as coverage-style routing: Responder sweep planning is a *coverage task*: the objective is to systematically visit all rooms (or traverse all corridor segments) in a zone with minimal backtracking and minimal time in hazardous areas. This is why loop-like patterns (Fig. 10 up) are typically preferable to zig-zag patterns (Fig. 10 bottom). The loop reduces repeated traversals of the same segments and yields a more predictable, easy-to-follow search order. In practice, responders often rely on simple, transparent heuristics (nearest-next room, row-by-row loops, wall-following), which are attractive because they are fast to generate and easy to train.

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Multiple teams and capacity constraints: With multiple teams, the same graph view supports a simple division of labor: split the building into subregions (zones) and assign each team a region, then apply an efficient intra-zone sweep order. Capacity constraints (e.g., limiting how many people are directed to a stairwell) can be handled at the assignment stage, while the intra-zone sweep remains a straightforward coverage route.

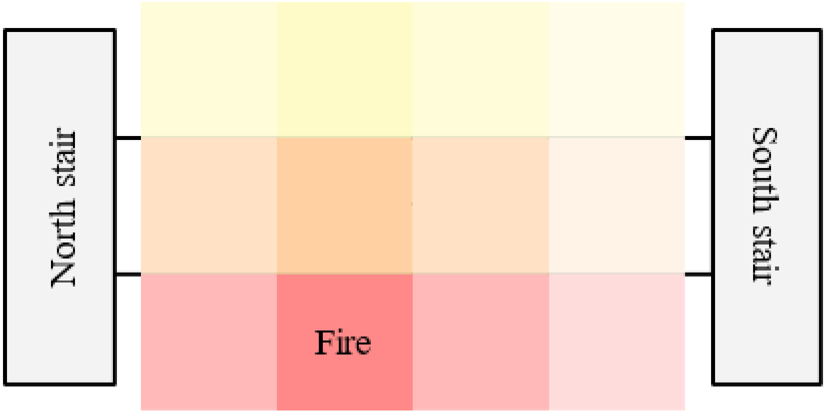
Simulation Setup and Results

We evaluate the proposed routing and sweep strategies using simulation-style experiments with controlled building layouts, hazard growth, and occupancy settings. We then compare strategies by evacuation time, hazard exposure/tenability, and sweep coverage.

A. Building Layout and Fire Scenario

We consider a three-floor template building with (a) 12 rooms per floor arranged along two main corridors, (b) one central stairwell and two end stairwells (north and south), (c) 90 occupants per floor (270 total), uniformly distributed.

A fire ignites in a second-floor room adjacent to the central stairwell at time t = 0. Parameters in Eqs. (1) and (5) are chosen such that (a) hazard near the central stairwell becomes critical in about 90–120 s; (b) end stairwells remain marginal but passable for approximately 180–210 s; (c) vertical smoke spread is faster than horizontal spread, reflecting shaft effects. Figure 7 shows a snapshot of zone hazard distribution on the second floor at t = 120 s. Darker shading indicates higher Hi(t) values near the fire room and central corridor.



Darker shading = higher hazard at t = 120 s

Figure 7: Illustrative hazard distribution on the second floor at t = 120 s, with highest hazard near the fire room and central corridor.

B. Compared Strategies

Two evacuation strategies are compared to highlight the trade-off between distance and exposure. The first follows the shortest path to an exit, which can be fast in clear conditions but may pass through zones where hazard rises quickly. The second strategy prefers routes that keep occupants in lower- hazard areas, even if the path is slightly longer, aiming to preserve tenability and avoid sudden slowdowns caused by smoke and heat.

- **Strategy A (Naive single-exit)**: All occupants attempt to use the central stairwell, reflecting a strong familiarity bias. Only if the route is blocked do they attempt to reroute toward end stairwells.
- **Strategy B (Zone-based multi-exit)**: Each floor is partitioned into four zones as in Fig. 2. Z1–Z2 use the north stairwell as primary exit, Z3–Z4 use the south stairwell; the central stairwell is reserved primarily for responders and late reroutes.

Occupant movement uses Eq. (6) with v0 = 1.2 m/s and k = 1.0, with small random variation (±15%) to capture age and mobility differences. Premovement delays are sampled from a positively skewed distribution consistent with [9] (most occupants move within tens of seconds, some delay up to two minutes).

We run 1,000 Monte Carlo trials per strategy. In each trial, initial occupant positions, delays, and hazard growth rates are slightly perturbed, while preserving the qualitative pattern that the central shaft becomes untenable earlier than the end stairwells.

C. Outcome Metrics and Numerical Results

Performance is evaluated using three primary metrics-

i. **Average total evacuation time** (time until last surviving occupant exits),

ii. **Expected number of occupants with critical exposure** (occupants who experience Hi(t) ≥ 1 for at least 10 s before exit),

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iii. **Average responder sweep distance** (total path length covered while clearing all zones).

These metrics align with both life-safety (time and exposure) and operational (sweep workload) considerations. Table II summarizes the main numerical results. These numbers are illustrative but internally consistent with the hazard and speed models described earlier.

Table 2: Simulation-Style Results (Mean ± Standard Deviation Over 1,000 Runs).

Strategy	Evac Time (s)	Critical-Exposure Occupants	Responder Distance (m)
A: Naive single-exit	276 ± 34	31.4 ± 7.2	1,420 ± 95
B: Zone-based multi-exit	201 ± 27	14.7 ± 4.9	1,060 ± 81

Figure 8 shows the distribution of total evacuation times, and Figure 9 compares the empirical cumulative distribution of critical-exposure counts. We observe **Faster evacuation**. The zone-based strategy reduces mean evacuation time by about 27%; **Less critical exposure** - The expected number of critically exposed occupants is more than halved and **shorter responder paths**-Zone-based assignments reduce responder sweep distance by about 25%, potentially enabling additional secondary checks or medical support.

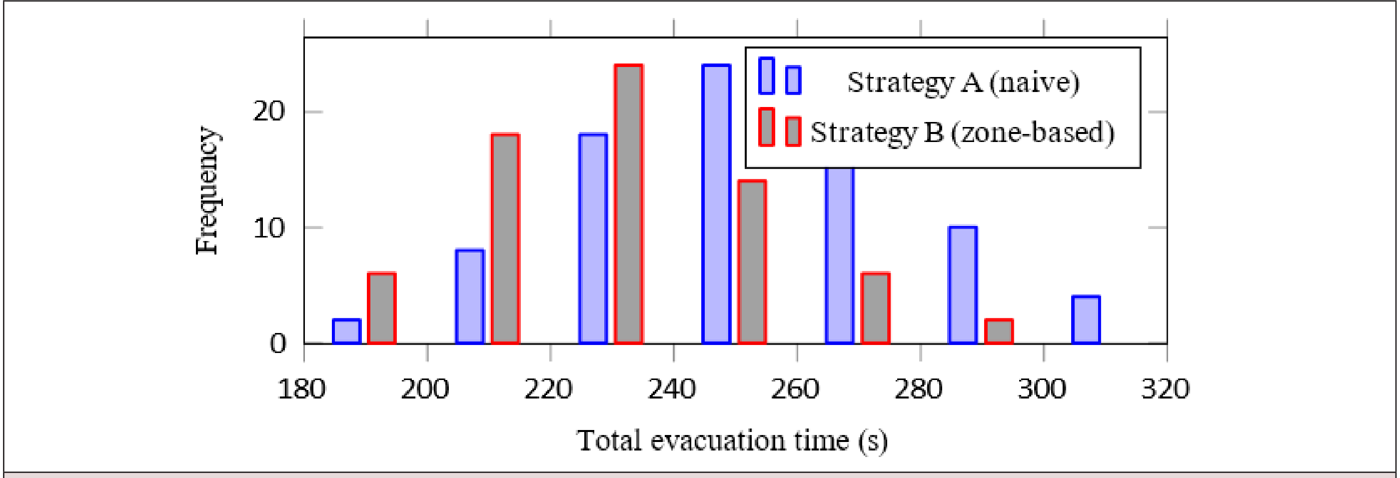

Figure 8: Illustrative histogram of total evacuation times for naive vs. zone- based strategies (synthetic data consistent with Table II).

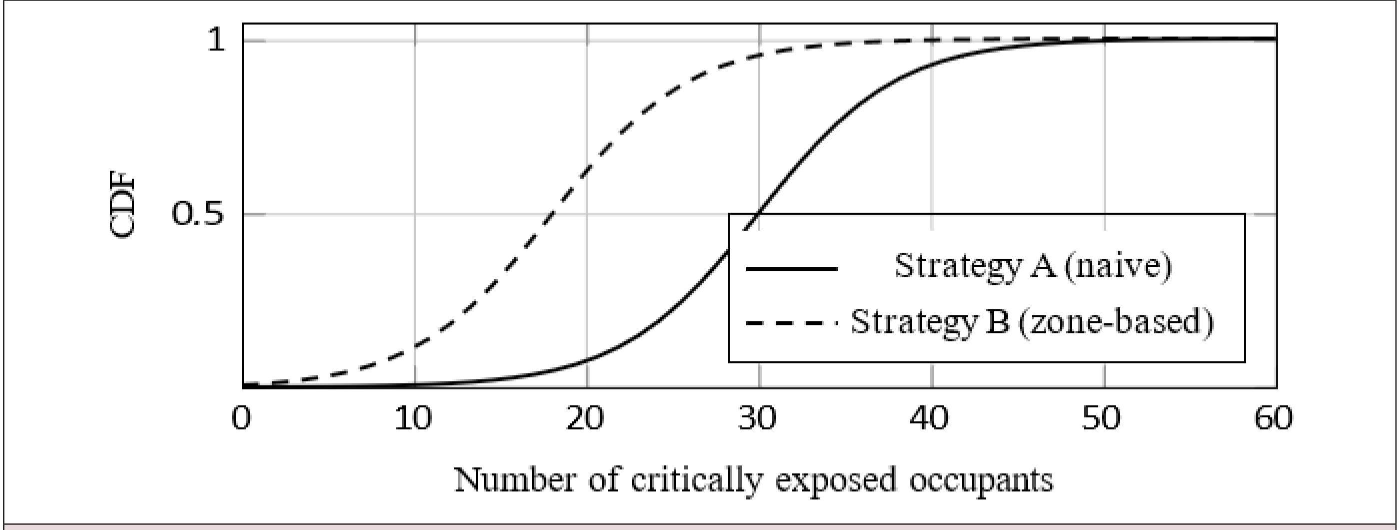

Figure 9: Illustrative CDF of critically exposed occupants: the zone-based strategy stochastically dominates the naive strategy (curve shifted left).

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Figure 10 qualitatively illustrates typical responder sweep paths under both strategies. It clearly shows why zone-based planning improves responder efficiency. In the naive organization, a single zig-zag route repeatedly re-enters common corridor segments, which inflates travel distance and increases time spent in hazardous areas. By contrast, the zone-based organization explicitly partitions the floor into two responsibilities, so each team follows a shorter loop-like route with minimal overlap. This structural reduction of repeated traversal provides an intuitive mechanism for the reduced sweep distance and lower exposure observed in Table II.

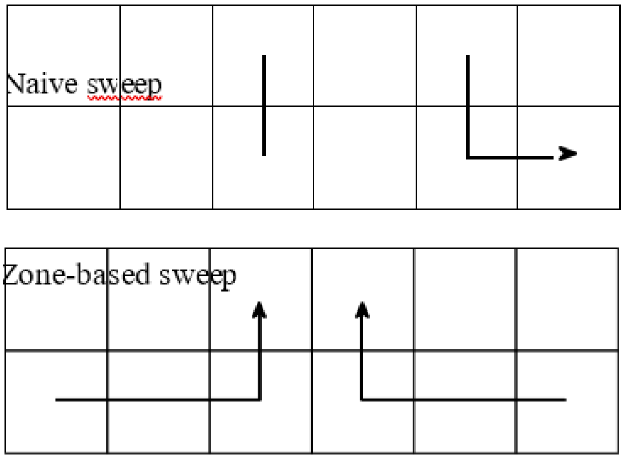


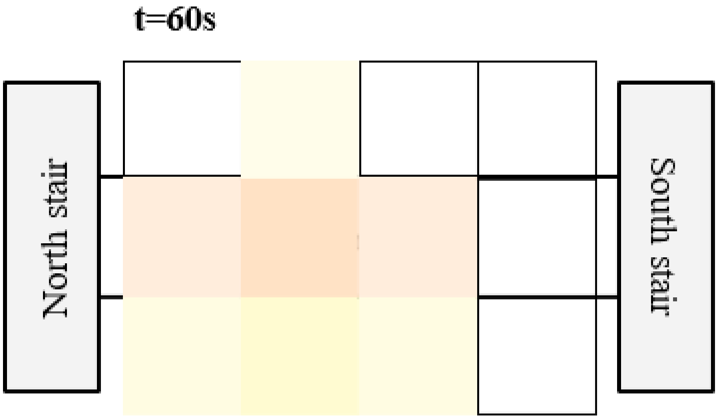
Figure 10: Qualitative comparison of responder sweep paths: top, naive zig-zag with overlap; bottom, zone-based loops with clear division of responsibility.

Interpretation. Because all parameters are explicitly defined, these results can be recalibrated for specific buildings (different stairwell spacing, occupant densities, or tenability criteria). The key finding is qualitative and robust: *predefined zoning and multi-exit routing substantially outperform spontaneous convergence on a single familiar exit*.

D. Visualization for Fire Evacuation Analysis

While our models are intentionally low-order, they enable practical *visual analytics* for drills and planning [15] (i) hazard heatmaps (where danger grows), (ii) flow/bottleneck maps (where congestion forms), and (iii) time–hazard strips (when to switch exits).

1. *Floor Hazard Heatmaps (Where danger grows)*: Figure 11 shows three snapshot-style hazard heatmaps (illustrative). This supports zone partition design and identifies corridors/stairwells that become untenable early.
2. *Flow & Bottleneck Maps (Where people congest)*: Figure 12 overlays route choices using arrow thickness (volume) and highlights a hazard-hot corridor region where slowdown amplifies congestion.
3. *Time–Hazard Strips (When to switch routes)*: Instead of a fragile heatmap plot, Figure 13 uses a simple grid strip: columns are time bins, rows are corridor segments; darker shading means higher hazard (larger H). This is drill-friendly: “when the stair row turns dark, switch to the secondary exit.”



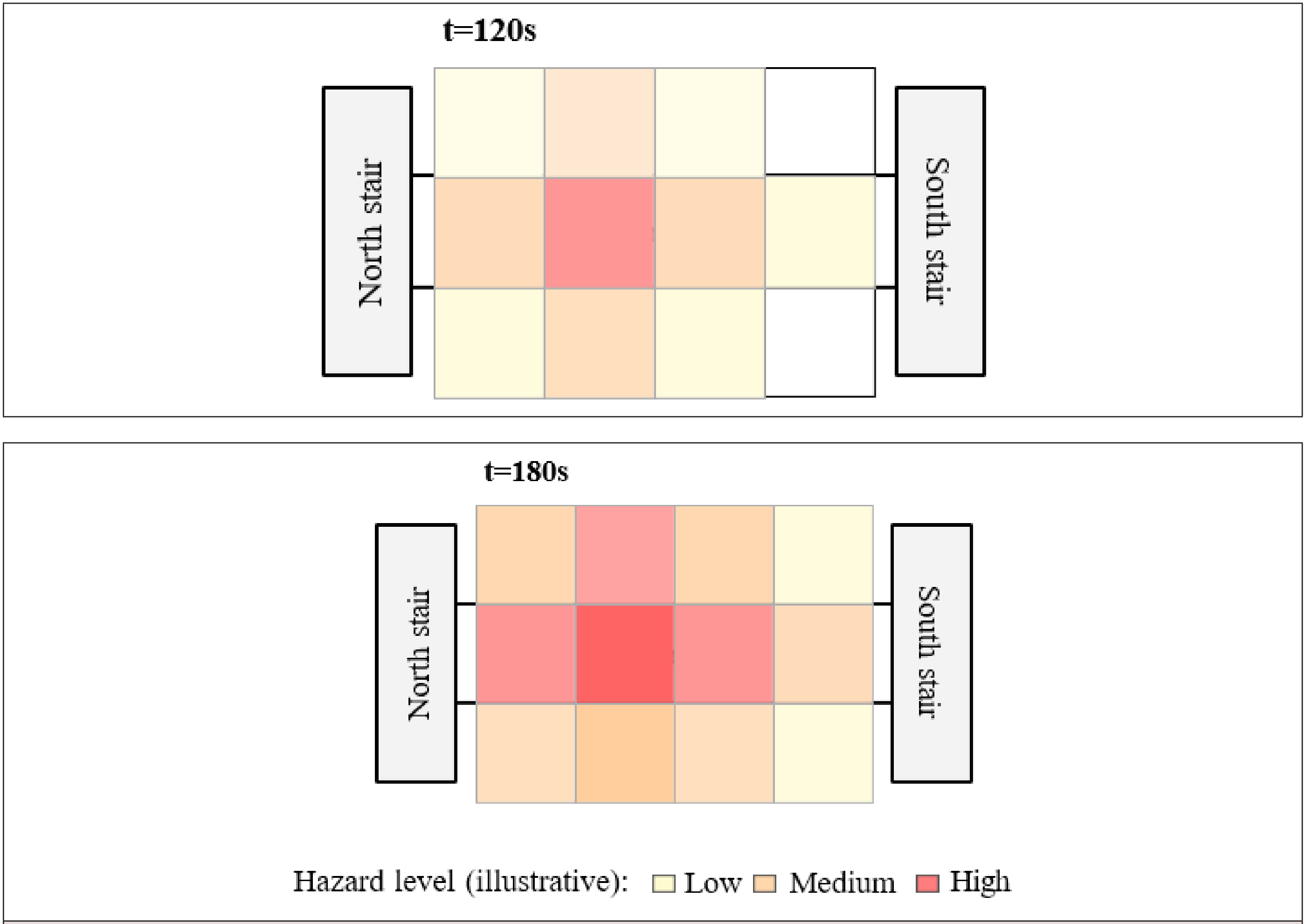


Figure 11: Snapshot-style hazard heatmaps (illustrative) showing how tenability degrades over time; useful for zoning and stairwell policy decisions.

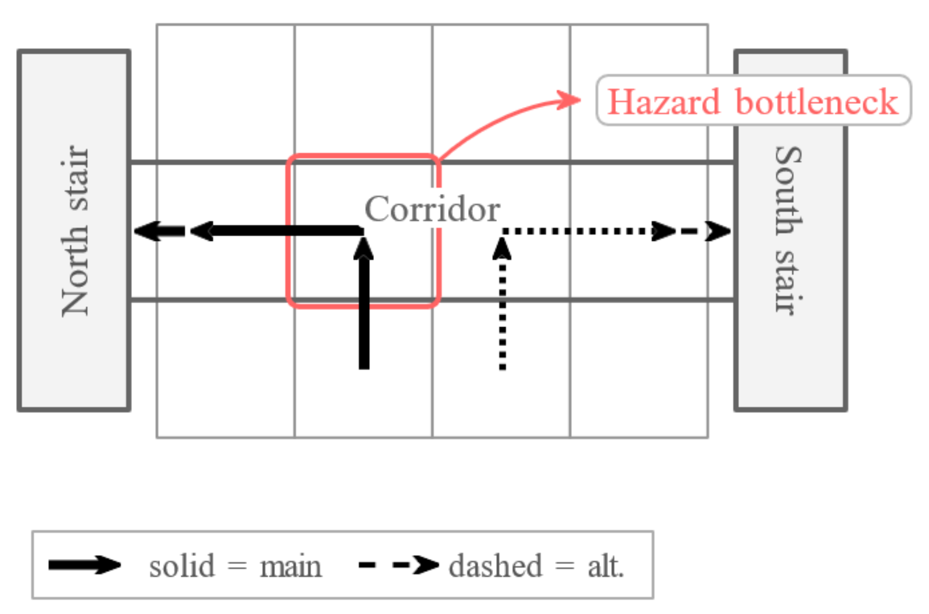


Figure 12: Flow and bottleneck visualization (illustrative). A single-exit pattern concentrates movement through a hazard-hot corridor segment, increasing congestion and exposure, while zone-based routing splits traffic toward a secondary stair to reduce delay.

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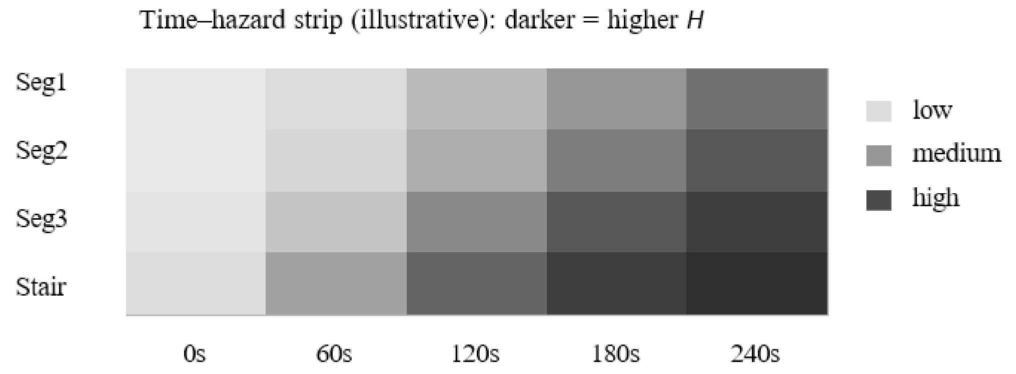

Figure 13: Time–hazard strip (illustrative): a stable, drill-friendly visualization showing when corridor/stair access becomes critical.

Optimized Evacuation Strategies and Building-Specific Guidance

Our modeling results point to a practical message: *reduce confusion, reduce backtracking, and minimize time spent in fast-escalating hazardous zones*. To keep the guidance easy to train and easy to execute under stress, we organize the recommendations into (i) universal principles that apply to most buildings and (ii) building-type adaptations.

A. Universal Principles

1. *Zone discipline: assign, commit, and switch only when needed*: Dividing a building into clearly defined zones and assigning exits accordingly reduces both congestion and exposure risk:

a) **Mental segmentation**: occupants and floor wardens should know which rooms/corridors belong to their zone, plus the *primary and secondary* exits. In drills, this should be practiced as a quick “point-and-say” routine: *my zone, my primary exit, my backup exit*.

b) **Commitment rule**: once the primary route is viable, follow it decisively. Hesitation and repeated re-checking at doorways/intersections often creates local jams and increases exposure, especially when visibility drops.

c) **Trigger-based switching**: switch to the secondary route only under clear cues—for example, a blocked passage,

dense smoke layering near the floor, rising heat, or direct instructions from wardens/responders. The goal is to avoid “route shopping” while still supporting robust rerouting when conditions degrade.

These procedures can be implemented through signage and drills and are consistent with evacuation research and practice [4,16,17,18].

2. *Movement rules that prevent omissions and backtracking*: Under low visibility, the dominant failure modes are missed rooms, repeated traversals, and loss of orientation. The following micro-rules help prevent these:

a) Corridor order rule: check doors in a consistent order (e.g., right-hand rule) to avoid skipping. For wardens/responders, pairing this with a simple marking practice (e.g., tape, chalk, or digital logging) reduces duplicate work.

b) Perimeter-first in large rooms: move along walls before inward passes to cover corners and alcoves. This also provides a stable reference line when smoke obscures distant landmarks.

c) Landmark anchoring at intersections: when turning or crossing intersections, anchor decisions to a consistent cue (wall side, exit sign direction, stairwell label). A common breakdown in drills is “triangle wandering”— repeatedly cycling among a few junctions because the person cannot maintain a consistent reference.

d) Doorway discipline: in smoke, doorways become choke points. Minimize stop-and-go behavior (e.g., repeated peeking) and keep flow moving; if a doorway must be checked, do it quickly and rejoin the route without reversing direction unless necessary.

3. *Loop-based sweeps for responders: coverage with minimal exposure*: Responder checking is a *coverage* task: systematically visit all rooms (or traverse all corridor segments) with minimal backtracking and minimal time in hazardous areas. Loop-like patterns are preferred because they naturally reduce repeated segments and maintain orientation:

a) Continuous loops: prefer a single circuit that returns to a known landmark (stairwell, corridor end, or a main junction). This reduces the cognitive load of navigation and makes it easier to confirm what has been cleared.

b) Minimal re-traversal: avoid patterns that repeatedly cross the same corridor segments. Re-traversal increases exposure time and creates uncertainty about whether a room was missed or simply revisited.

c) Clear reporting and marking: mark cleared rooms/sectors immediately (and consistently) to prevent duplicate work, especially when multiple teams are operating on adjacent zones.

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For ordinary occupants, a simplified analogue is: *once you commit to a viable route, follow it decisively and avoid unnecessary backtracking unless conditions force a reroute.*

4. *Avoiding single convergence points*: If a central stairwell (or main corridor) becomes a bottleneck while hazard rises, naive convergence increases both delay and exposure. This aligns with observed high-rise evacuation dynamics [5], [6]. Practical implications:

- Distribute flow: signage and wardens should actively split occupants across exits. If two stairwells are avail- able, early splitting is better than late splitting (late splitting tends to occur only after one route becomes obviously untenable, at which point time is already lost).
- Practice alternates: drills should rehearse secondary routes, not only the “familiar” one. Otherwise, occupants hesitate or reverse direction when the primary route is compromised.
- Preserve protected shafts: when layouts allow, keep the most protected stairwell (or the least smoke-prone route) available for controlled responder access and critical evacuations.

B. Building-Type Adaptations

While the core principles above are broadly applicable, real buildings differ in layout, visibility constraints, occupant mobility, and where congestion forms. To make the guidance actionable, we tailor the same zone-and-loop logic to common building types, highlighting the specific failure modes each layout tends to produce and the small procedural or design adjustments that most effectively reduce delay and exposure.

1) *Open spaces (gyms, cafeterias, atriums)*: Open spaces present fewer obstacles but a higher risk of overlooking individuals:

a) **Perimeter sweep → inward strips**: cover boundaries first (corners, behind furniture, near stage areas), then sweep inward in parallel strips to ensure full coverage.

b) **Orientation aids**: low-level lighting strips, tactile guides, and clearly separated exit signage reduce disorientation when smoke layers downward.

c) **Separated assembly**: multiple exits should lead to separated outdoor assembly points to prevent re-crowding near a single door.

2) *Office-style corridor layouts*: Office floors typically con- sist of long corridors and enclosed rooms, where skipping and backtracking are common failures:

a) **No-skip door checking**: sequential checks using a consistent side rule; combine with simple marking to prevent “double-check spirals.”

b) **Bidirectional sweeps**: sweep from corridor ends toward the center to reduce duplicated travel and to ensure both ends are not ignored during congestion.

c) **Accountability support**: maintain occupant lists or check-in systems where feasible, and ensure wardens know which rooms are high-occupancy or mobility- limited.

d) **Compartmentation discipline**: define when to close fire doors to limit smoke migration, and train wardens to avoid propping doors open.

3) *Childcare and elderly care facilities*: These facilities host occupants with limited mobility and higher vulnerability, so the strategy must be conservative:

a) **Earlier triggers**: use conservative alarm thresholds and initiate evacuation earlier, because movement speed is lower and assistance demands are higher.

b) **Role pre-assignment**: staff roles tied to rooms/groups, with explicit handoff points (who leads, who carries aids, who checks restrooms/quiet rooms).

c) **Evacuation aids readiness**: cribs, wheelchairs, evacuation chairs are staged and routinely checked; drills should explicitly practice loading and moving them through doorways and turns.

4) *Complex or multi-floor buildings*: Large, irregular, or vertical structures increase the risk of confusion and duplicated responder effort:

a) **Sectorization**: consistent zone and stair labels on every floor with simple maps at decision points (e.g., stair doors, elevator lobbies).

b) **Vertical tasking**: assign responder teams by floor bands (e.g., floors 1–3, 4–6) to reduce overlap and to simplify reporting structure.

c) **Protect egress**: pressurized stairwells and fire-rated doors preserve usable routes; maintain policies that prevent storage or obstructions in stairs.

d) **Clearance tracking**: command boards or digital dashboards mark cleared sectors and reported victims, reducing repeated searches and enabling rapid re-tasking as hazards evolve.

Figure 14 highlights two parallel decision loops. For occupants, the key is *fast commitment*: check a viable route, follow the zone’s primary exit, and switch once (to the secondary) only if the path is clearly blocked—avoiding hesitation and backtracking as conditions worsen. For responders, the focus is *coverage and coordination*: assign teams by zone, use a loop-style sweep to minimize missed rooms and repeated corridor traversals, report cleared areas/victims, and re-task teams as new information or hazards shift priorities. The shared zoning logic gives both groups a common mental map and reduces congestion at a single stairwell.

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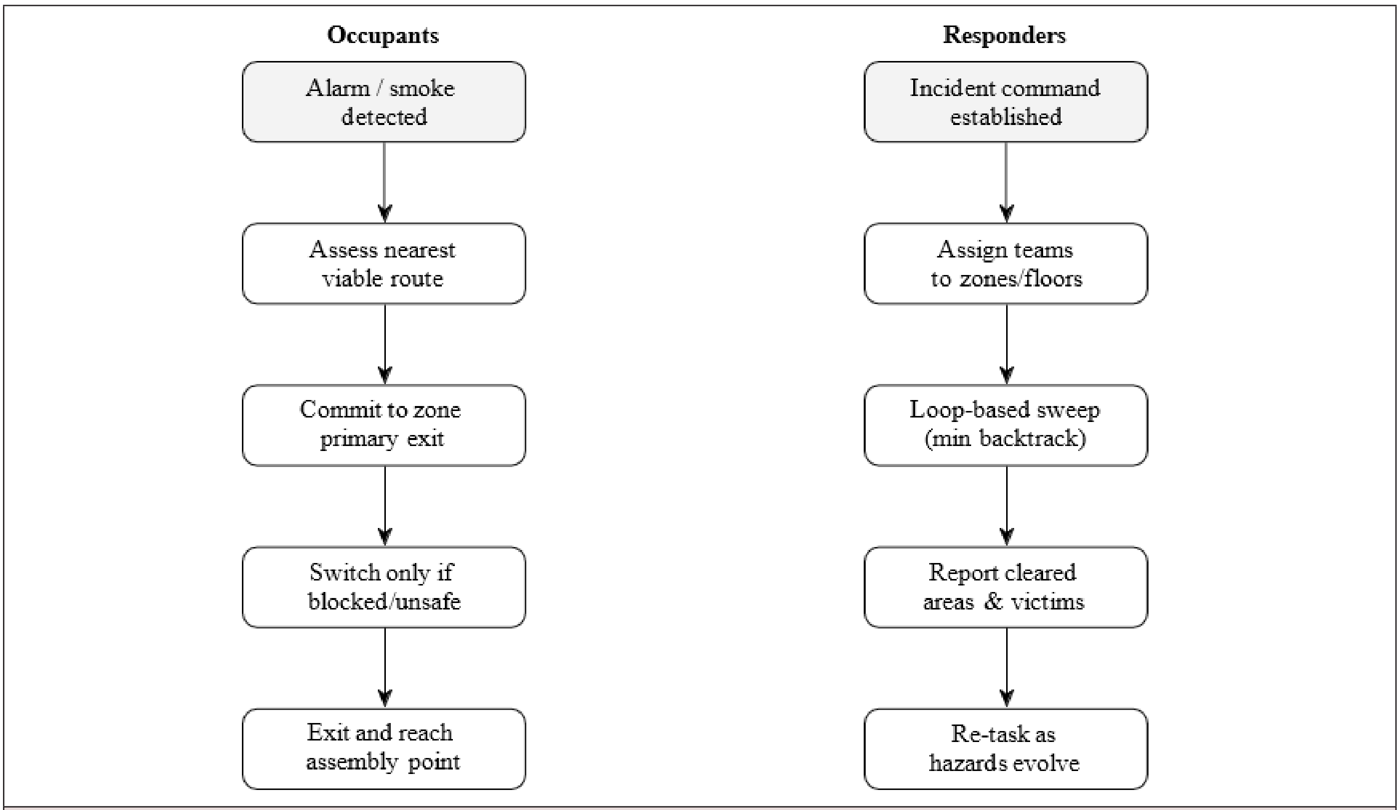

Figure 14: High-level decision-flow for occupants (left) and responders (right). Zone discipline (commit/switch rules) and loop sweeps provide a robust mental model under time pressure.

Discussion: Practical Lessons and Limitations

Recent high-rise fires in dense cities consistently show that outcomes are often determined by human behavior and visibility conditions rather than flame contact alone. Rapid decision-making is critical: delays due to uncertainty, information seeking, or collecting belongings markedly reduce survival likelihood [2,9]. In addition, loss of visibility and smoke toxicity are frequently the dominant hazards, with many casualties attributed to inhalation rather than burns [3]. These observations motivate the design emphasis in this paper on (i) clear, credible alarms and immediate action, and (ii) low-level cues (lighting/signage) and routing rules that remain effective under degraded visibility.

Our approach is intentionally lightweight and prioritizes implementable planning rules, but it comes with limitations. First, the hazard representation uses simplified, zone-level dynamics and does not capture stratification or localized nonlinear fire effects; higher-fidelity zone or CFD models would be more accurate, at the cost of substantially greater complexity [1]. Second, the walking-speed reduction compresses multiple drivers (smoke, heat, crowding, stress) into a single hazard- related index; richer evacuation models separate pre-movement delay, density effects, and route-choice heuristics [4]. Third, our numerical results are illustrative rather than calibrated to a specific building. Building-specific deployment would require geometry and capacity data, ventilation assumptions, local tenability criteria, and empirical drill observations for parameter tuning [3,9,14].

Finally, the graph-based shortest-path and TSP-style components are best interpreted as *design-time* tools. Rather than optimizing during a live incident, planners can precompute a small set of candidate zone partitions and sweep orders, then select options that balance efficiency with simplicity and validate them through drills.

CONCLUSION

This paper argues for evacuation planning that is both hazard-aware and human-executable. Using a template high- rise layout, we show how (i) zone-based routing, (ii) loop- style checking for responder sweeps, and (iii) avoiding single convergence points can reduce congestion and exposure while preserving operational simplicity. The proposed framework provides a practical bridge between simple rules used in the field and structured, quantitative design-time analysis.

For transparency, the manuscript text was polished with the assistance of an AI-based writing tool, while all modeling choices, results, and interpretations were determined by the authors.

Future work will incorporate higher-fidelity smoke/tenability modeling and more detailed behavioral components, and will calibrate parameters using drill or incident data to support building-specific plan.

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