

Pedestrian Flow Optimization in a University Building during Emergency Evacuation

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1 Introduction

Ensuring the safe and efficient evacuation of people from public buildings is a critical challenge, particularly in emergency situations such as fires. In university buildings, where large numbers of occupants are distributed across classrooms, lecture halls, and common areas, poor evacuation design can lead to congestion, increased evacuation times, and severe safety risks. Understanding how pedestrian flows propagate through such indoor environments is therefore essential for improving both architectural design and emergency response planning.

In this project, we optimize pedestrian evacuation in a simplified university building during a fire emergency. The main objective is to determine how occupants should be routed through the building in order to minimize the total evacuation time while maximizing the number of people reaching the exit. Special attention is given to realistic constraints specific to emergency situations: elevators are assumed to be unavailable, ramps are preferred over stairs, and corridor capacities reflect physical limitations. The problem is formulated as a minimum-cost flow model, enabling the identification of bottlenecks and the assessment of how building design affects evacuation performance.

2 Problem Description and Assumptions

We study the evacuation of occupants from a university building during a fire emergency, modeled as a simplified network of interconnected areas. The model focuses on key structural features that influence pedestrian movement rather than exact architectural details.

2.1 Building representation

The building is represented as a directed network $G = (V, E)$, where each node corresponds to a physical area of the building (e.g., hall, corridor junction, classroom, staircase, exit) and each directed edge represents a corridor or passage allowing pedestrians to move from area to area. Edges are directed to reflect pedestrian movement toward the exit, located at the southern end of the building. Each corridor has a fixed capacity representing the maximum flow of people per unit of time, accounting for physical constraints such as width and accessibility.

2.2 Emergency scenario

We focus on a fire emergency scenario in which all occupants aim to evacuate the building as quickly as possible. The following assumptions are made:

- Elevators are unavailable and therefore excluded from the network.
- Ramps are preferred to stairs, as they allow faster and safer movement.
- Stairs are allowed but penalized to reflect slower and more difficult movement.
- Occupants behave rationally, without panic or counterflow, and aim to minimize evacuation time.

The evacuation occurs over a short time horizon, during which the building structure and corridor capacities remain unchanged.

2.3 Modeling assumptions

To keep the model tractable, pedestrian movement is modeled as a continuous flow with constant walking speed. Individual interactions, panic behavior, and dynamic changes in corridor conditions are not explicitly modeled. Congestion effects are captured through corridor capacity constraints, and all occupants are assumed to follow the optimized evacuation paths.

2.4 Objective of the study

The objective of this study is twofold: (i) maximize the number of occupants reaching the exit and (ii) minimize total evacuation time, defined as the sum of individual travel times. By combining these objectives within a network flow framework, the model helps identify critical corridors, bottlenecks, and design limitations affecting evacuation efficiency.

3 Mathematical Model

In this section, we present the mathematical formulation of the evacuation problem. The model is based on a network flow framework and is designed to determine an optimal distribution of pedestrian flows that minimizes total evacuation time while respecting physical constraints.

3.1 Decision variables

For each directed edge $(i, j) \in E$, we define the decision variable

$$x_{ij} \geq 0, \quad (1)$$

where x_{ij} represents the number of people per minute moving from node i to node j during the evacuation.

3.2 Parameters

For each edge $(i, j) \in E$, we define:

- u_{ij} : capacity of corridor (i, j) (people per minute),
- T_{ij} : travel time associated with edge (i, j) .

Travel time is defined as

$$T_{ij} = \frac{L_{ij}}{v} + \gamma_{ij}, \quad (2)$$

where L_{ij} is the corridor length, v is the average walking speed, and γ_{ij} is a penalty depending on the type of passage:

$$\gamma_{ij} = 0 \text{ for ramps,} \quad \gamma_{ij} = \alpha > 0 \text{ for stairs.}$$

Elevator links are not included in the network.

3.3 Objective function

We minimize the total evacuation time experienced by all occupants:

$$\min F(x) = \sum_{(i,j) \in E} T_{ij} x_{ij}. \quad (3)$$

This objective encourages pedestrians to use shorter and safer paths, while penalizing routes involving stairs when alternatives are available.

3.4 Constraints

Capacity constraints.

$$0 \leq x_{ij} \leq u_{ij} \quad \forall (i, j) \in E. \quad (4)$$

Flow conservation constraints. For every node $k \in V$ that is not the exit node S , the incoming flow equals the outgoing flow:

$$\sum_{i:(i,k) \in E} x_{ik} = \sum_{j:(k,j) \in E} x_{kj} \quad \forall k \in V \setminus \{S\}. \quad (5)$$

Evacuation flow. The total number of evacuated people per unit time is the total flow entering the exit node:

$$F_{\text{out}} = \sum_{i:(i,S) \in E} x_{iS}. \quad (6)$$

3.5 Model interpretation

This formulation corresponds to a minimum-cost flow problem, where flows represent evacuated pedestrians, corridor capacities limit congestion, and travel times (including penalties) define the cost of each path.

4 Solution Method

We solve the evacuation optimization problem using a network flow approach combined with linear optimization techniques. The model corresponds to a minimum-cost flow problem, which can be solved efficiently due to its network structure.

4.1 Network flow formulation

The university building is modeled as a directed graph, where nodes represent building areas and edges represent capacity-limited corridors with associated travel times. The objective is to determine corridor flows x_{ij} such that total evacuation time is minimized, corridor capacity constraints are satisfied, flow conservation holds at intermediate nodes, and total flow reaching the exit is maximized.

4.2 Optimization approach

The problem is solved using a minimum-cost flow algorithm, which simultaneously maximizes the number of evacuated occupants and minimizes total evacuation travel time. In practice, this corresponds to a linear programming problem with a network structure.

4.3 Implementation

The model is implemented in Python using the NetworkX library. The main steps are: construction of the directed graph representing the building, assignment of corridor capacities and travel times, definition of the exit node as the sink, computation of the optimal flow, and visualization and interpretation of the results.

4.4 Graphical representation

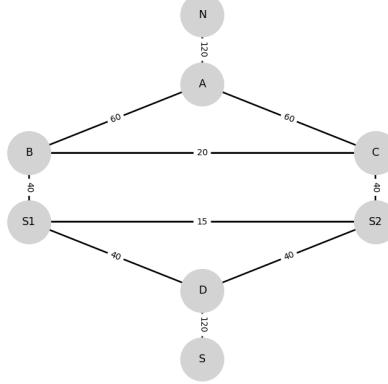


Figure 1: Directed graph representation of the university building. Nodes correspond to building areas and edges represent corridors. Edge labels indicate corridor capacities in people per minute.

5 Emergency Scenario and Experimental Setup

In this study, we focus on a single emergency scenario in order to provide a clear and detailed analysis of evacuation dynamics under constrained conditions.

6 Emergency Scenario and Experimental Setup

We consider a fire emergency scenario in which all occupants must evacuate the building as quickly as possible. Elevators are unavailable, ramps are preferred to stairs (which incur a time penalty), and corridor capacities remain fixed. As a baseline, all corridors are available at nominal capacity. A disruption scenario is then considered, in which the corridor connecting the main hall to the western wing is removed from the network, representing smoke propagation or localized fire.

6.1 Evaluation criteria

We evaluate: (i) total evacuation time (optimal objective value), (ii) total evacuated flow (number of people reaching the exit per unit time), and (iii) flow redistribution when a corridor is unavailable.

7 Results

7.1 Baseline evacuation results

We first analyze the baseline evacuation strategy, where all corridors are available at nominal capacity. Although entrance and exit areas have high capacity, evacuation is constrained by internal corridors, especially those linking classrooms and lecture halls to the stair and atrium area, which emerge as natural bottlenecks. The optimal flow is relatively balanced between the eastern and western wings, with crosslinks helping redistribute traffic and reduce congestion.

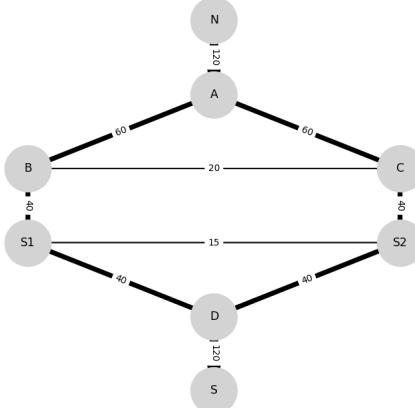


Figure 2: Optimal evacuation flows under baseline conditions. Edge thickness is proportional to the optimized pedestrian flow on each corridor, while edge labels indicate corridor capacities.

7.2 Disruption scenario: corridor closure

We next analyze the disruption scenario where the corridor linking the main hall to the western wing is closed, significantly modifying the evacuation network. Evacuated flow decreases and total evacuation time increases compared to the baseline. Pedestrian traffic is rerouted through the eastern wing and crosslinks, leading to increased congestion and rapid saturation of alternative paths. While crosslinks partially mitigate the disruption, they cannot fully compensate for the lost capacity.

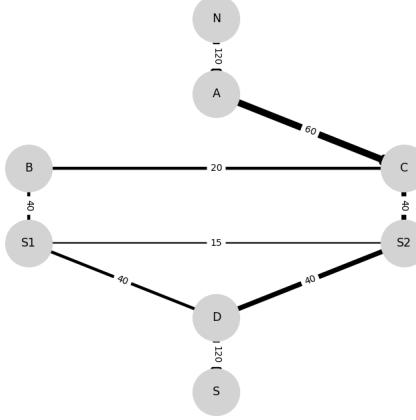


Figure 3: Optimal evacuation flows after closing corridor A→B. Edge thickness is proportional to the optimized pedestrian flow, and labels indicate corridor capacities.

7.3 Comparative analysis

Comparing the baseline and disrupted scenarios provides insight into the robustness of the building layout. Closing a single corridor significantly degrades evacuation performance, showing that some links are critical to the network. From an evacuation planning perspective, these results suggest prioritizing certain corridors for fire protection and smoke control, reinforcing alternative evacuation routes, and increasing capacity or accessibility in key areas.

8 Discussion and Limitations

The results demonstrate the usefulness of network flow optimization for evacuation analysis, showing how building layout and critical corridors affect evacuation efficiency. The approach is simple, interpretable, and computationally efficient, and can be adapted to different buildings or scenarios. However, it relies on simplifying assumptions (continuous flow, perfect compliance, static corridor conditions) and does not capture individual behavior or dynamically evolving hazards such as smoke propagation.

9 Conclusion

We analyzed emergency evacuation in a university building using a network flow optimization approach. By modeling the building as a directed network with capacity and travel-time constraints, the evacuation process was formulated as a minimum-cost flow problem balancing speed and safety. The disruption scenario confirms that closing a single corridor can significantly worsen evacuation outcomes, highlighting the need for redundancy. Future work could incorporate dynamic conditions, multiple exits, or more realistic pedestrian behavior.

Code availability: <https://github.com/clemencemorin/Optimization-Project>