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Evaluating Office Layout Effects on Evacuation Time Using Social Force Model

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I, Robin Song, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the work.

Date: August 17, 2025

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Signature:

Abstract

This study systematically investigates how internal spatial configurations in office spaces — specifically desk layout, corridor width, number of exits, and door width — influence the efficiency of orderly evacuation under fixed building constraints. We conduct multi-scale agent-based simulations within a coupled Rhino 9 with Grasshopper and JuPedSim workflow, constructing two prototypes (Small and Big) and comparing island layouts (A, B, C), various corridor/door width combinations, and single vs. double exits. Preliminary trajectory data are used to derive metrics such as speed, path length, Total Evacuation Time (TET), and congestion hotspots. Results indicate that internal layout significantly affects congestion hotspots and path choices, with door-corridor width coupling showing threshold effects and scale dependence, especially in the Big prototype. Temporal/spatial patterns are analyzed via heat maps, density distributions, and time-series analysis; robustness is evaluated via repeated simulations. Data are stored in SQLite databases with metadata to ensure reproducibility.

Acknowledgements

Acknowledge all the things!

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Chapter 1

Introduction

1.1 Research Background

In increasingly dense office spaces, the efficiency of emergency evacuations is directly related to personnel safety. Although considerable research has focused on crowd dynamics and evacuation simulations, the engineering challenge of optimizing evacuation paths and reducing congestion through systematic adjustments of internal layouts, within the constraints of fixed building structures, remains unresolved.

1.2 Research Question

This study aims to systematically explore the impact of internal spatial geometric configuration parameters (such as table layout, corridor width, number of exits and door width, etc.) on the efficiency of orderly evacuation of building space under the constraints of fixed building structure. The research will focus on the following key issues: How does the layout of tables affect evacuation efficiency and path formation; The marginal effect of corridor width and exit parameters on evacuation dynamics and the regulatory role of congestion patterns; The influence of the Gate waidth before exit on the formation of the path, and the relationship between the evacuation time distribution and the path distribution under different gate width configurations.

Through the simulation of two scale Office prototypes, it reveals how these internal layout parameters systematically regulate the evacuation process, in order to provide data-driven optimization suggestions for the safety design of office.

Chapter 2

Literature Review

2.1 JuPedSim

JuPedSim (Julich Pedestrian Simulator) is an open-source software framework for pedestrian dynamics and personnel evacuation simulation, aiming to study the movement and evacuation behaviors of people in the built environment through computer simulation. This tool takes ”self-driven multi-agent system” as its core concept, modeling each pedestrian as an independent agent. The agents follow a set of rules in a given scene to determine their own movement path, speed and interaction behavior, thereby presenting phenomena such as flow, congestion, queuing and path selection at the group level at the macro level. JuPedSim is often coupled with microscopic simulation models such as the classic Social Force Model. By setting parameters such as the input geometric scene, entrance/exit conditions, channel width, and density, a quantitative evaluation of the evacuation performance in a specific scene can be obtained.

2.2 Social Force Model

In simulations of emergency evacuation scenarios, researchers usually employ modeling methods such as social force models, cellular automata as well as agent-based models to simulate the complexity of crowd behavior. These models have become the primary approach in this field of study. The social force model is an appealing method because it offers a relatively open and scalable framework. Compared to other models, the social force model can more intuitively explain the interactions between individuals and can replicate complex phenomena in crowded environments, such as speed, density and queuing situations. This model was first introduced by Helbing and Molnár in 1995, attempting to accurately simulate crowd behavior from a microscopic dynamics perspective, analogous to gas dynamics. Its core idea is to view crowd movement as a dynamic process influenced by various ”forces”. Many researchers have continuously improved and applied the social force model, further expanding its potential. For example, Zheng and others combined the social force model with neural networks to simulate collective behavior in different scenarios; Seyfried and colleagues made modifications to pedestrian dynamics for qualitative analysis; Parisi and Dorso utilized this model to study the evacuation process in rooms with exits. These studies indicate that the social force model has become an important tool for simulating crowd movement, showing broad application prospects especially in areas like traffic planning and architectural design.

2.3 Rhino and Grasshopper

The study's modeling and simulation workflow are conducted in Rhino 9 WIP, using Rhino as the geometry and initial agents placement environment. Grasshopper serves as the parametric front-end to drive the simulations, passing geometric inputs (polylines, doors, corridors, etc.) as point lists to the agent-based simulation instance. Grasshopper is extended via Python scripting to enable seamless integration with JuPedSim. A Python 3.13 environment is used to write the bridge scripts that map Rhino/Grasshopper geometry to JuPedSim input scenes and to extract trajectories, speeds, congestion metrics, and other diagnostics from JuPedSim outputs for downstream analysis. We didn't use Rhino before version 9 WIP because it is the first version that supports Python 3.13(Rhino 8's Python is 3.9), which is required by JuPedSim.

2.4 Previous Work

An important branch of evacuation simulation is the research on physical environmental factors. The key elements of spatial structure include the geometric form of buildings, exit configuration and the distribution of obstacles. The geometric form of buildings involves the shape of rooms, floor height and corridor width, and these parameters directly affect the possibility and efficiency of crowd movement. Exit configuration, including the number, location and width of exits, is a key factor in determining the evacuation speed. In addition, the distribution of obstacles, such as the spatial positions of fixed facilities like tables, chairs and columns, significantly affects the evacuation paths and crowd speeds .

In 2012, Ma et al. conducted experimental research on evacuation in China's skycrappers, focusing on the impact of building physical characteristics on the evacuation process. Peacock and Kuligowski (2004) systematically reviewed occupant movement in buildings and found that physical environment factors, including space configuration, exit placement, and obstacle distribution, significantly affect evacuation efficiency. Koo et al. (2013) compared evacuation strategies in high-rise buildings, particularly examining the paths of disabled individuals under different physical conditions. Their study revealed that the geometry and design of exits directly determine the feasibility and safety of evacuations. In high-density and emergency situations, these physical factors can greatly influence crowd behavior during evacuations. A common conclusion from these studies is that the physical environment is a significant influence on evacuation simulation, necessitating a comprehensive consideration of building shape, exit quantity and location, stair width, and obstacle distribution.

In research on classrooms and office spaces, while exit design is important, an increasing number of studies highlight the significant impact of internal furniture arrangement, desk layout, and corner configurations on evacuation efficiency. In some situations, these internal layout factors can outweigh the influence of exit width or quantity (Liu, Parhizgar, 2018;). Helbing et al. specifically emphasized the considerable effect of obstacles, such as desks in a classroom, on evacuation efficiency. These findings indicate that optimizing layout by adjusting internal environmental parameters can significantly alter crowd path choices and congestion hotspots.

2.5 Research Gap

Despite the extensive research on evacuation simulations, there is still a lack of systematic exploration of how internal layout parameters affect evacuation performance in fixed structural settings.

Firstly, existing studies lack a systematic analysis of how internal layout parameters interact. Most of the studies only focus on single parameter such as number of exits and layout of desks and seats, while ignoring factors including corners, corridor width and door width as well as their interaction, particularly in senarios with multiple exits and neted rooms.

Secondly, there is a lack of research on prototypes with different sizes. The lack of reliable methods for scaling from small and simple spaces to large and complex layout limits the translation of research results into practical applications.

Third, current research primarily focuses on simple scenarios such as classrooms, while systematic studies on the layout of office spaces are relatively scarce. Unlike traditional scenarios like classrooms, office spaces exhibit a high degree of complexity, including densely populated crowds, diverse furniture configurations, and dynamic layouts. The uniqueness of office spaces lies in the relatively fixed initial positions of personnel and the significant flexibility of furniture arrangements. Therefore, changes in the layout of office spaces may significantly impact evacuation efficiency, making them an ideal subject for evacuation simulation research.

Based on the aforementioned research limitations, the innovation of this study lies in: under the fixed structural constraints of office space scenarios, systematically comparing the evacuation performance of different scales and multiple layout variants, and revealing the coupling effects of door width, corridor width, and exit configuration through quantitative analysis. This research not only provides an actionable method for assessing the safety of office spaces but also offers a new methodological perspective for evacuation simulation studies.

Chapter 3

Methedology

3.1 System integration and technology stack

3.1.1 Objectives and Framework

This research achieved parametric coupling of Rhino 9's Grasshopper with JuPedSim, using Grasshopper to represent office floor geometry (polylines as point lists) and initial agent positions(points). A Python script will call JuPedSim's API to map the geometry from Rhino to the input for the JuPedSim scene, utilizing a social force model for microscopic simulations within Rhino.

3.1.2 Technology Stack and Versions

Rhino 9 (Grasshopper) + Python (3.10+, meeting JuPedSim's compatibility requirements);
JuPedSim (Julich Pedestrian Simulator) and its Social Force Model;
Data analysis and processing: JupyterLab + Python (Pandas, NumPy, Matplotlib/Seaborn, SQLAlchemy/sqlite3);
Data storage and playback: Each simulation outputs an SQLite database file for offline playback and statistical analysis.

3.1.3 Input and Output Description

Input: Office geometry (polylines representing contours, doors, corridors, etc.), initial agent positions (Grasshopper point sets), and scene parameters (island table layout, corridor width, number of exits, door widths, etc.).

Output: Each simulation round outputs the raw trajectory data as a SQLite file, while derived metrics such as speeds, congestion events, and other diagnostics are computed from these trajectories for subsequent analysis. Metadata (version, environment, random seed, etc.) are recorded as part of the analysis workflow.

Figure 3.1: Data Pipeline

3.2 Experimental design

3.2.1 Prototype Scales

Small prototype: Focus on the preliminary effects of layout on evacuation paths and times, with rapid iteration through smaller geometric dimensions. Big proto-

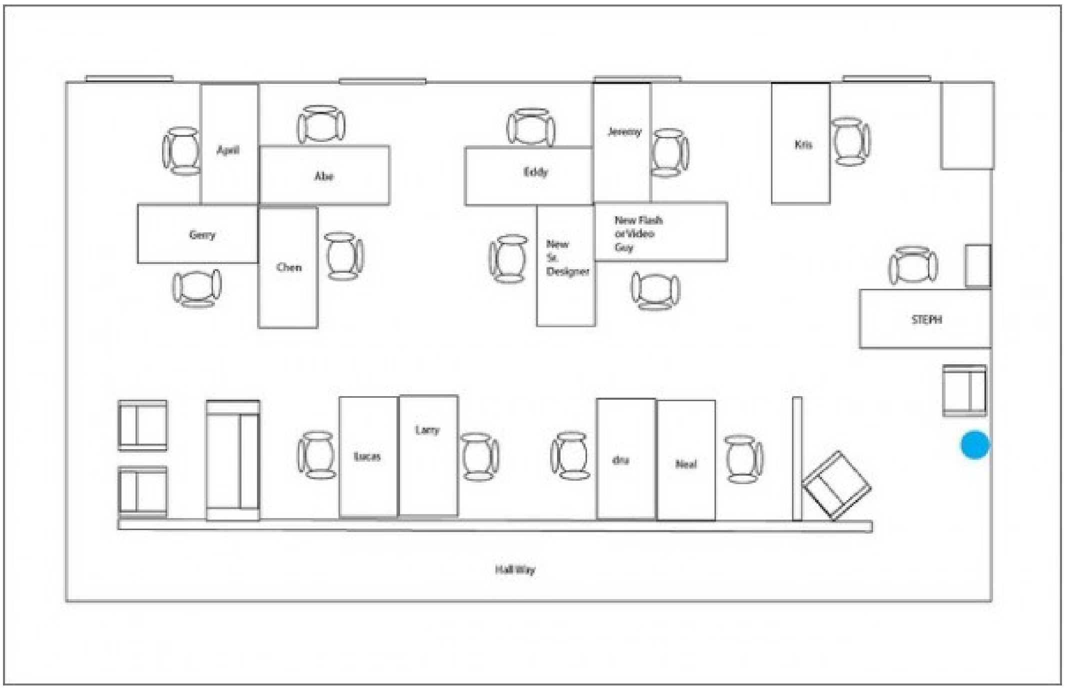

Figure 3.2: Small Prototype

type: Introduce higher-level issues such as door width coupling and multi-room nesting, testing the coupling effects at scales closer to actual office spaces.

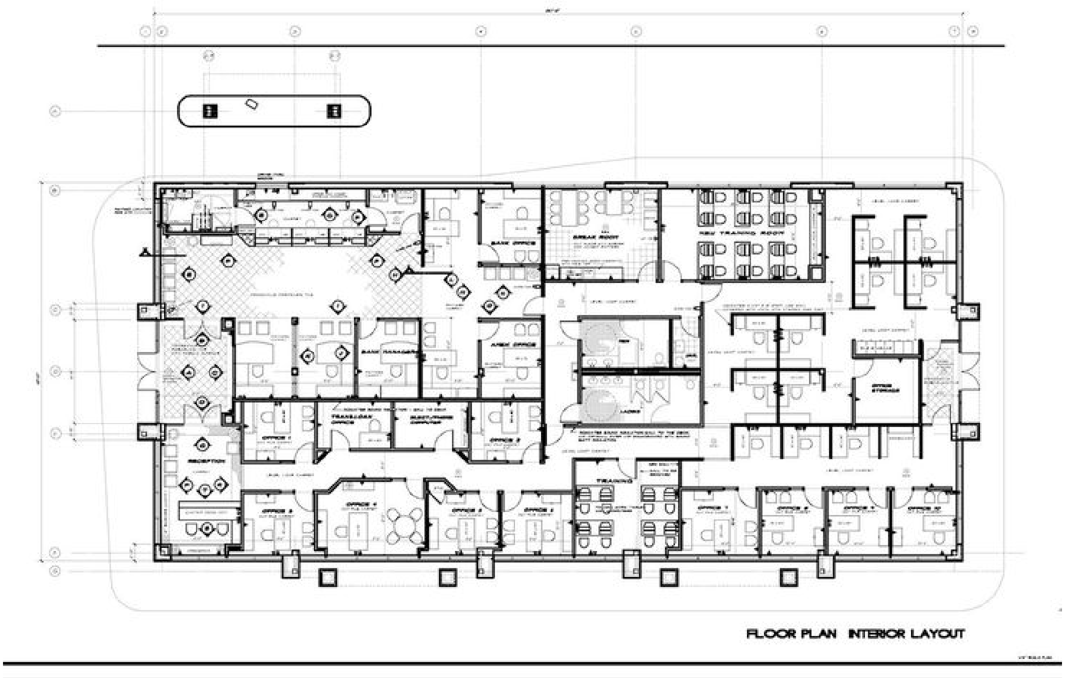

Figure 3.3: Big Prototype

3.2.2 Randomness and Replication

Each parameter configuration is repeated 5 times, with initial positions randomly sampled from a Grasshopper point set to reduce the impact of randomness on the results.

3.2.3 Variable Design

Island Table Layout: Three variants A, B, and C represent the internal furniture configuration's representative parameters.

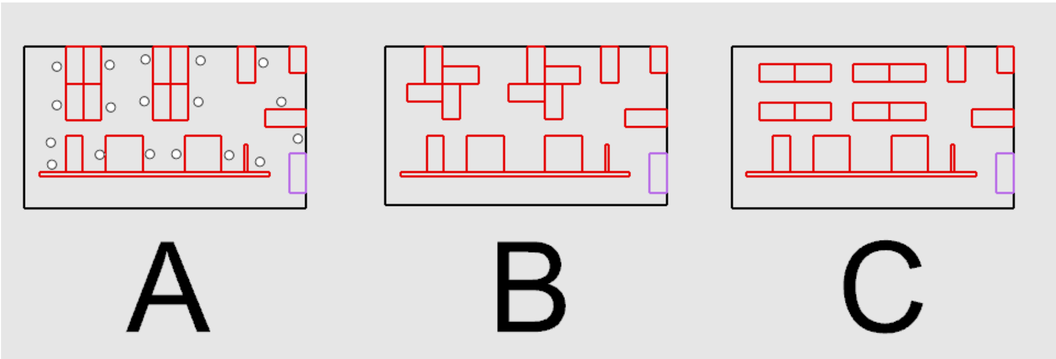

Figure 3.4: Island Table Layout

Corridor Width: 0.8 m, 1.2 m, 1.6 m, 2.0 m, 2.4 m (covering key intervals from small to large to facilitate the identification of marginal effects and potential thresholds).

Exit Configuration: Single exit and double exit, comparing the impact of different exit quantities on path formation and congestion.

Additional Variables for Big Prototype: Door width (Gate Width) ranging from 1.0 m to 1.6 m to explore the sensitivity of early congestion and flow distribution; combinations of room door widths and corridor door widths in multi-room coupling scenarios.

3.3 Agents and Model Settings

This section focuses on clearly setting and recording the attributes of agents (pedestrians), the initial distribution, and the key parameters of the Social Force Model (SFM) within the JuPedSim framework, ensuring comparability and repeatability between different configurations.

Figure 3.5: Corridor Width

3.3.1 Agent Attributes and Initial Conditions

Initial Agent Quantity and Distribution: The total number of agents is set in the Grasshopper/JuPedSim scene input based on the scale of the scenario, with the initial distribution (Grasshopper point set) controlling the initial quantity and spatial distribution.

Initial Position Mapping: The point set of Grasshopper is mapped to the initial coordinates of the agents, ensuring that the randomness of initial positions between different configurations is controllable and that repeated experiments can be replicated.

Goals and Behavioral Tendencies: Defaults are uniformly set, but in scenarios

Figure 3.6: Exit Configuration

with multiple entrances, agents tend to choose the shortest path.

3.3.2 Social Force Model Parameters

Model Framework: The built-in Social Force Model of JuPedSim is used as the core microscopic simulation model.

Desired Speed: 0.8 m/s is set as the default value, with sensitivity analysis within a range (e.g., 0.6–1.0 m/s) conducted as needed.

Interaction Force Parameters: These include repulsive forces between agents, repulsive forces against obstacles, and response intensity to queuing and group aggregation. The initial settings adopt the official recommended values from

JuPedSim.
Obstacle Handling and Boundary Conditions: The obstacle force scale is set to 1000 to balance the resistance to obstacles in complex scenarios, preventing excessive suppression of agent movement. Boundary conditions follow the wall and exit definitions in the geometric input of the scene.

3.4 Data collection and Analysis

3.4.1 Data Output and Storage

Each simulation produces an independent SQLite database file, recording agent trajectories, speeds, positions, and scene metadata for easy playback and offline analysis.

3.4.2 Data Reading and Processing

Use JupyterLab and Python to read SQLite files (sqlite3), organizing the data into an analyzable structure (DataFrame), and aggregating and statistics on time steps, agent attributes, congestion indicators, etc.

3.4.3 Indicators

Primary indicators: Total Evacuation Time (TET), Average Path Length, Path Distribution Characteristics, Congestion Hotspot Distribution (Heatmap/Density Map).
Secondary indicators: Path Formation Patterns (Single Lane Flow, Arch-Shaped, Bottleneck Queueing), Variance of Repeated Intervals, Path Diversity, etc.

3.4.4 Statistical Analysis

For different layouts, corridor widths, exit configurations, and door widths, use ANOVA, t-tests, or non-parametric methods for comparison; analyze interactions between variables (significance of interaction terms) and potential nonlinear thresholds.
Use regression analysis/generalized linear models to assess the coupling effects of variables such as door width, corridor width, and number of exits on the

intensity of their impact on evacuation time and congestion distribution.

3.4.5 Results Presentation and Visualization

Create path density maps, histograms of evacuation time distributions, heatmaps of congestion hotspots, and comparative bar charts under different configurations. Combine with example trajectory playback to demonstrate path evolution and congestion points in specific scenarios.

Chapter 4

Result and Discussion

4.1 Overview

4.2 Small Prototype

4.2.1 Effect of Workstation Islands Arrangement

TET and Mean Path Length vary with island layout (A, B, C).

Figure X.Y shows TET across layouts (n = 5 repeats).

Path density maps and trajectory map indicate shifts in hotspot locations with layout.

4.2.2 Effect of Corridor Width

TET and congestion metrics as a function of corridor width (0.8-2.4 m) within each island layout.

Identify potential thresholds where congestion reduces notably.

4.2.3 Effect of Number of Exits

TET and congestion metrics with single vs. double exits.

Compare path formation and congestion under different exit configurations.

Identify exit configurations that minimize congestion and optimize evacuation times and find the nonlinear coupling between exit width and corridor width.

4.3 Big Prototype

4.3.1 Effect of Gate Width Before Exit

Gate Width vs TET curves; focus on edge cases in narrow corridors.

Congestion hotspot changes with gate width.

4.3.2 Coupling Effect of Corridor Entrance and Passage Width

Interaction heatmaps of corridor entrance width × passage width on TET and congestion.

Marginal effects demonstrate where coupling amplifies or mitigates congestion.

Chapter 5

Conclusion and Limitation

5.1 Conclusions

In this study, we systematically compared Small and Big office prototypes across island layouts A, B, C and varying corridor widths, door/gate widths, and exit configurations. The results show nonlinear coupling between geometry and flow, with scale-dependent sensitivity observed in the Big prototype under narrow corridors. Key findings include:

5.2 Limitations

5.2.1 Model and Parameter Sensitivity

Our results show threshold-like responses to key parameters (e.g., gate width, corridor width). Small changes near intrinsic model thresholds can lead to disproportionately large effects, especially in the Big prototype.

5.2.2 Discretization of Parameter Space

The parameter grid is sampled at discrete values, and behavior near thresholds may differ from interpolations between points. Caution is needed when generalizing beyond tested values.

5.2.3 Generalizability and External Validity

This reasearch is based on JuPedSim and Social Force Model, while Real-world validity may be limited by model assumptions (e.g., homogeneous agents, static furniture). External validation with empirical evacuation data is needed.

5.3 Practical Implications and Cautions

Designers should beware of relying on discrete parameter choices. Critical points near thresholds may drive large changes in performance; validate with site-specific constraints. However, our workflow was built in Rhino, which allows designers to reproduce the simulations easily as needed to verify results or test alternative layouts.

5.4 Future Work

Expand to include alternative models (e.g., cell-based or agent-based with different interaction rules), add external validation with real evacuation data, explore more layouts and furniture configurations, increase repeats, and consider uncertainty quantification

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