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Optimizing Evacuation in Densely Populated Buildings: A Bottleneck Analysis

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Highlights

- Integration of evacuation considerations into the densely populated buildings is emphasized.
- Pathfinder simulations revealed stair bottlenecks in the Ordu Annex Courthouse.
- 95% of occupants evacuated within 316 seconds; bottlenecks delayed the remaining 5%.
- Optimizing stairwells, widening corridors, and adding flow-control elements are recommended.

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Abstract

Safe and efficient evacuation from densely populated buildings during emergencies is crucial for ensuring human safety. This study analyzes potential evacuation bottlenecks in densely populated buildings using the newly constructed Ordu Annex Courthouse in Turkey as a case study. Employing Pathfinder simulations, pedestrian flow dynamics were modeled, and critical areas of congestion hindering evacuation efficiency were identified. The simulation results revealed that while 95% of occupants could evacuate within 316 seconds, the remaining 5% experienced significant delays, particularly due to bottlenecks at stairwells leading to exits. This finding highlights the importance of evacuation optimization in the design of densely populated buildings. The study proposes actionable design recommendations, such as adjustments to corridor widths, modifications to exit configurations, and strategic placement of flow-control elements, as strategies with the potential to improve evacuation times and enhance overall safety.

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1. INTRODUCTION

Densely populated buildings have become an indispensable part of modern urban life. Structures such as shopping malls, educational institutions, hospitals, stadiums, office buildings, and courthouses play significant roles in our daily lives, while also posing distinct safety challenges due to their capacity to host large crowds. During emergencies, the safe and efficient evacuation of these buildings becomes a critical factor that can save countless lives [1, 2]. Unforeseen events like fires, earthquakes, or terrorist attacks can put a strain on building evacuation systems and lead to unpredictable human behaviors.

In densely populated buildings, the collective movement of individuals seeking safe egress during an emergency can quickly escalate into panic and chaos [3]. Congestion on evacuation routes can cause people to bunch up at doors, leading to crush risks. In such chaotic situations, prolonged evacuation times significantly increase the risk of injury and loss of life. An effective evacuation plan is essential to minimize these risks and ensure that all occupants can safely exit the building.

Another factor that complicates evacuation planning for densely used buildings is user diversity [4]. These buildings can accommodate individuals of different age groups, physical abilities, and varying levels of familiarity with the building layout [5]. For instance, a shopping mall might have people using wheelchairs, individuals with visual impairments, the elderly, children, and tourists trying to evacuate simultaneously. An evacuation plan that does not reflect this diversity may cause some groups to be left behind and

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endangered. Designing an inclusive evacuation plan that considers the specific needs and potential limitations of each user is vital for ensuring the safe evacuation of all individuals.

Psychological factors are also known to significantly affect evacuation processes during emergencies [6]. Stress and uncertainty can impair people's ability to think rationally and make decisions, leading to panic, indecision, and erratic movements [7]. This can result in congestion on evacuation routes and the "faster is slower" effect, where the effort of individuals to move faster can actually slow down the evacuation due to collisions and falls [8]. Therefore, evacuation planning must also consider these aspects of human behavior and develop strategies to minimize the risk of panic.

One of the most significant factors endangering evacuation safety in densely used buildings is the presence of bottlenecks [9, 10]. Bottlenecks are areas where pedestrian flow is restricted, and people accumulate. As such, bottlenecks can significantly extend evacuation times and increase the risk of crushing. Narrow corridors, inadequate exit capacity, the convergence of multiple corridors into a single point, door orientation, and obstacles on evacuation routes can contribute to bottleneck formation [11, 12]. Identifying these potential bottleneck points during the design phase and taking necessary precautions is crucial for evacuation efficiency and safety [13].

This study presents a simulation-based approach to analyze evacuation bottlenecks in densely used buildings and to develop optimization strategies. Using the newly built Ordu Annex Courthouse in Turkey as a case study, pedestrian flow dynamics were modeled using Pathfinder simulation software [14]. The main objectives of this study are to identify critical congestion areas on the evacuation routes of the Ordu Annex Courthouse, to evaluate the evacuation performance of the building under different scenarios, and to provide actionable design recommendations to improve evacuation times and enhance overall safety.

This study aims to emphasize the importance of evacuation optimization in the design and operation of densely used buildings, thereby making a significant contribution to ensuring the safety of building occupants. The rest of the paper is structured as follows: section 2 comprehensively examines the concept of bottlenecks and how they are addressed in evacuation scenarios in the literature. Section 3 explains in detail the methodology used for bottleneck analysis during evacuation. Section 4 presents the steps for applying this methodology to the selected case study, along with an introduction to the relevant case. Section 5 focuses on the findings obtained from the case study. Section 6 examines and discusses the relationships between the findings from the simulation studies. Finally, section 7 discusses the conclusions of the paper and the broader significance of these results.

2. LITERATURE REVIEW

Safe and efficient evacuation from densely populated buildings is a complex process involving various disciplines, including architectural design, human behavior, and emergency management. Extensive research in this field provides valuable insights for informing evacuation planning and implementation. This section reviews key findings and approaches in pedestrian dynamics, bottleneck analysis, and evacuation optimization, establishing the theoretical framework for this study.

2.1. Pedestrian Dynamics and Bottlenecks

Pedestrian dynamics is a field of study that draws from disciplines such as physics, mathematics, and social psychology to understand the movement and behavior of individuals in crowds [15]. This field focuses on understanding how people move, make decisions, and interact with each other and their environment during an emergency evacuation. The primary focus of pedestrian dynamics research is the study of bottlenecks, which restrict pedestrian flow and cause congestion on evacuation routes [9].

In densely populated buildings, bottlenecks can significantly extend evacuation times, increasing the risk of injury and loss of life. A significant factor affecting bottleneck formation is the width of the bottleneck [16]. Wider passages generally allow for a higher flow rate, while narrow passages can cause congestion. However, this relationship is not always linear. A phenomenon known as the "zipper effect" allows people

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in adjacent lanes to merge efficiently at the bottleneck, maximizing the use of available space and increasing the flow rate [9]. The length of the bottleneck also affects evacuation time, especially when combined with factors such as user density and movement motivation [11]. Longer bottlenecks can cause queues and delays by keeping pedestrians in a confined area for extended periods.

The shape, angle, and curvature of a bottleneck can also significantly affect flow dynamics [17]. For example, funnel-shaped bottlenecks have the potential to improve pedestrian flow and are particularly effective in high-density areas [18]. However, it has been found that the optimum angle depends on pedestrian density and the width of the approaching corridor, requiring design solutions to be customized to specific scenarios [19]. Obstacles near bottlenecks can also affect flow [5]. Strategically placed obstacles can act as flow regulators, disrupting the formation of dense crowds and improving flow [8, 20]. However, poorly positioned or oversized obstacles can increase congestion and extend evacuation times [21, 22].

Various metrics are used to measure the severity of bottlenecks and their impact on evacuation efficiency. Pedestrian density refers to the number of people in a given area, and high density restricts freedom of movement, thereby extending evacuation times [23, 24]. Walking speed indicates the speed of pedestrian movement, and high density and bottlenecks reduce walking speed, slowing down evacuation. Time headways represent the time interval between successive pedestrians, and bottlenecks reduce time intervals, restricting pedestrian flow.

A characteristic phenomenon associated with bottlenecks is the "arching effect," which is a curved shape that forms at bottlenecks in dense crowds [8, 25]. This arching, documented through experimental studies [26], can obstruct flow and, especially when combined with pedestrian impatience or competitive behavior, increase the risk of crushing or injury [27]. Research has shown that factors such as increased walking speed and changes in the direction of movement, common in panic situations, can further amplify the "faster is slower" effect associated with arching and bottleneck congestion [28, 29].

2.2. Building Design and Evacuation

Building design significantly impacts evacuation efficiency and safety. Factors such as the location, number, and width of emergency exits, the size and layout of corridors, stair design, and signage and lighting can affect evacuation times. International and national building codes and standards (e.g., NFPA 101, [30]; Regulation on Fire Protection of Buildings, [31]) provide general guidelines for evacuation route design, exit capacities, and signage. However, these guidelines often specify minimum requirements and may not fully address the unique needs of specific building types and usage scenarios.

Densely used buildings host various user profiles, and evacuation planning should reflect this diversity. For example, individuals with disabilities, the elderly, and children may need additional assistance or special arrangements during an evacuation [5]. To meet these needs, designers should incorporate features such as accessible exits, escort services, and clear and understandable signage and lighting.

Designers should also consider the psychological factors that influence human behavior during evacuations. Under stress and uncertainty, people may panic, lose their ability to think rationally, and make dangerous decisions [7]. To minimize these effects, designers can use clear and intuitive signage and lighting to make exit routes clear and understandable, make evacuation instructions and procedures clear and easily accessible, and use calming environmental design elements to encourage staying calm and orderly during an evacuation.

2.3. Evacuation Modeling and Simulation

Modeling and simulating building evacuations allow designers to test different scenarios, identify potential bottlenecks, and evaluate the effectiveness of evacuation plans. Various simulation software such as Pathfinder, buildingEXODUS, and STEPS are available [32, 33]. These software can be used to model pedestrian movement, behavior, and building geometry to estimate evacuation times, density, and other

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metrics. Simulation results can help designers optimize evacuation routes, reduce bottlenecks, and improve the overall safety of evacuation plans.

This literature review presents the fundamental concepts and approaches necessary to understand evacuation dynamics in densely used buildings. Building on this knowledge base, this study examines the Ordu Annex Courthouse as a case study and addresses evacuation optimization.

3. RESEARCH METHOD

This study employs a systematic and multifaceted methodology to analyze evacuation bottlenecks and develop optimization strategies in densely populated buildings. The methodology, illustrated in Figure 1, includes stages such as architectural analysis, determination of occupant load, simulation modeling, scenario analysis, model validation, and data analysis. The Ordu Annex Courthouse serves as a case study for the implementation of this methodology. This section explains in detail the steps and methods used in the study.

The first step is to conduct a comprehensive analysis of the physical and architectural features of the building under study, along with its usage patterns. This analysis is crucial for understanding the evacuation processes and potential bottlenecks. The building analysis includes the following steps:

- **Reviewing Architectural Drawings:** The floor plans, sections, facade views, and other architectural drawings of the building are meticulously examined. This review aims to determine the general layout of the building, the location of corridors and staircases, the number and distribution of exits, the placement of doors and windows, and the presence of potential obstacles (furniture, equipment, structural elements, etc.).
- **Analysis of Usage Patterns:** The daily operation and usage patterns of the building are analyzed to create a realistic basis for evacuation scenarios. This analysis includes determining the peak hours of the building, the distribution of different user groups (employees, visitors, etc.), typical circulation routes, and user density in specific areas (e.g., meeting rooms, waiting areas, cafeteria).
- **Assessment of Access Control:** The building's security protocols, access-controlled areas, and how they affect access to emergency exits are examined in detail. This stage involves determining the access rights of different user groups to specific areas, the placement of security checkpoints, and security measures that may hinder access to emergency exits.

Following the building analysis, a digital model of the building is created using the chosen simulation software (Pathfinder in this study), and the necessary parameters for the evacuation simulation are defined.

- **Creation of the Building Model:** The architectural drawings of the building are transferred to Pathfinder software, creating a detailed 3D model including walls, corridors, staircases, exits, and other significant architectural elements. This model represents the virtual environment where pedestrians move during the simulation.
- **Defining User Profiles:** User profiles are created to represent the movement and behavior patterns of different user groups that may be present in the building during an evacuation. These profiles may differ in terms of walking speed, reaction time, exit choice preferences, and other factors. For instance, young and healthy individuals may walk faster, while elderly or disabled individuals may move slower. User profiles are crucial for enhancing the realism of the simulation and evaluating the evacuation performance of different groups more accurately.
- **Setting Simulation Parameters:** Various parameters are adjusted to ensure the simulation operates realistically. These parameters include:
    - **Maximum Walking Speeds:** The maximum walking speed to be applied to each user profile is determined. These speeds can be based on data found in the literature, observations, or experimental studies [23].
    - **Collision Avoidance Rules:** Rules used to prevent pedestrians from colliding with each other during the simulation are defined. These rules allow pedestrians to maintain their personal space and adjust their movements to avoid collisions.
    - **Exit Selection Algorithms:** Algorithms that determine which exit pedestrians will choose are defined. These algorithms can consider the distance to the exit, the density of the exit, the user's familiarity with the building, and other factors [34].

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- **User Density:** The user density to be used in the simulation environment is determined. This density can be adjusted to reflect the normal usage conditions of the building or emergency scenarios.

Accurately determining the building's maximum occupant load is critical for a realistic evacuation simulation. In this study, the internationally recognized NFPA 101 Life Safety Code standards were used to calculate the occupant load [30]. NFPA 101 provides specific occupant load factors (area per person) for different types of spaces (e.g., offices, meeting areas, etc.). These factors vary according to the function, purpose of use, and typical furniture layout of the space. For example, the occupant load factor for an office area might be 9.3 square meters (gross) per person, while for an assembly area, it might be 0.65 square meters (net) per person. These factors form the basis for calculating the maximum occupant load for each area and ensure the simulation model is realistically calibrated.

To evaluate the evacuation performance of densely populated buildings under different conditions, multiple simulation scenarios are created and run by varying factors such as potential emergencies (e.g., fire, earthquake), user distribution, and exit capacity. These studies allow us to understand how different scenarios affect evacuation times, congestion levels, and other metrics.

To ensure that the simulation model accurately reflects real-world conditions, a model validation phase is implemented. In this phase, simulation results are compared with real-world data, literature findings, and expert opinions to assess the model's validity. Experts (e.g., architects, fire safety engineers, emergency management specialists) can review the simulation model and results, providing feedback on realism and applicability. After completing the simulation studies, the obtained data are analyzed and interpreted. This data provides information on evacuation times, congestion levels, exit usage, and pedestrian movement patterns, and is used to develop actionable recommendations to enhance evacuation safety in densely populated buildings.

4. CASE STUDY: ORDU ANNEX COURTHOUSE

In this study, the newly constructed Ordu Annex Courthouse in Turkey was chosen as a case study to analyze evacuation bottlenecks in densely populated buildings. Using Pathfinder simulation software [14], the evacuation performance of the building was evaluated under different scenarios.

4.1. Flowchart of the Study

Figure 1 provides a flowchart summarizing the methodology of the study. The process begins with a detailed building analysis where architectural drawings are examined to understand the building layout, user profiles, and potential evacuation routes. Subsequently, occupant load calculations are made according to NFPA 101 Life Safety Code [30]. An agent-based modeling approach is used for the evacuation simulation, and different maximum walking speeds are assigned to different user profiles to represent varying mobility levels. Finally, design recommendations are developed to improve evacuation efficiency based on the simulation results.

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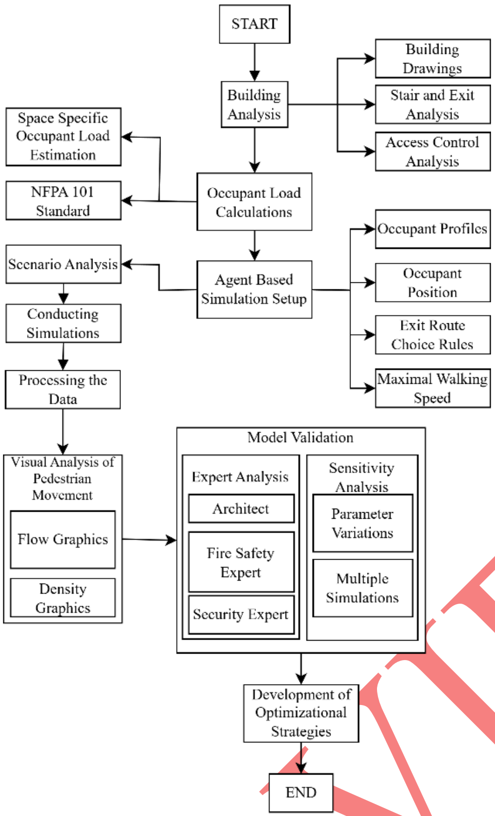

Figure 1. *Flowchart of the Study*

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4.2. Building Description and Architectural Analysis

A thorough understanding of the physical characteristics of the Ordu Annex Courthouse is crucial for accurate evacuation modeling. This section presents a detailed architectural analysis, focusing on elements affecting pedestrian flow, including the location and capacity of exits, dimensions of corridors and stairways, and potential obstacles.

Building Layout and Access Control

The building consists of a basement, four floors above ground, and a terrace floor (fifth floor), as shown in the 3D model (Figure 2). To enhance realism, the simulation model was constructed based on the actual structure of the courthouse. The building is divided into four distinct sections:

- **Public Area:** This section, comprising waiting areas, courtrooms, and public units (bank, post office, cafeteria), is open to all users.
- **Employee Area:** Accessible only to courthouse employees (office workers and judges), this area requires authorized access (card system).
- **Judge Area:** Access is further restricted in these areas, with only judges permitted entry (card system).
- **Detainee Area:** This area is reserved for detainees and accompanying law enforcement personnel. It includes dedicated circulation paths between the detention rooms in the basement and the courtrooms on the upper floors (card system).

These four sections are indicated on the plan with different color codes (Figure A8). Figure 2 shows the ground floor plan of the Ordu Annex Courthouse. The building consists of multiple sections with different access levels and uses. Detailed information about the building layout, access control measures, and other floor plans are provided in Appendix A.

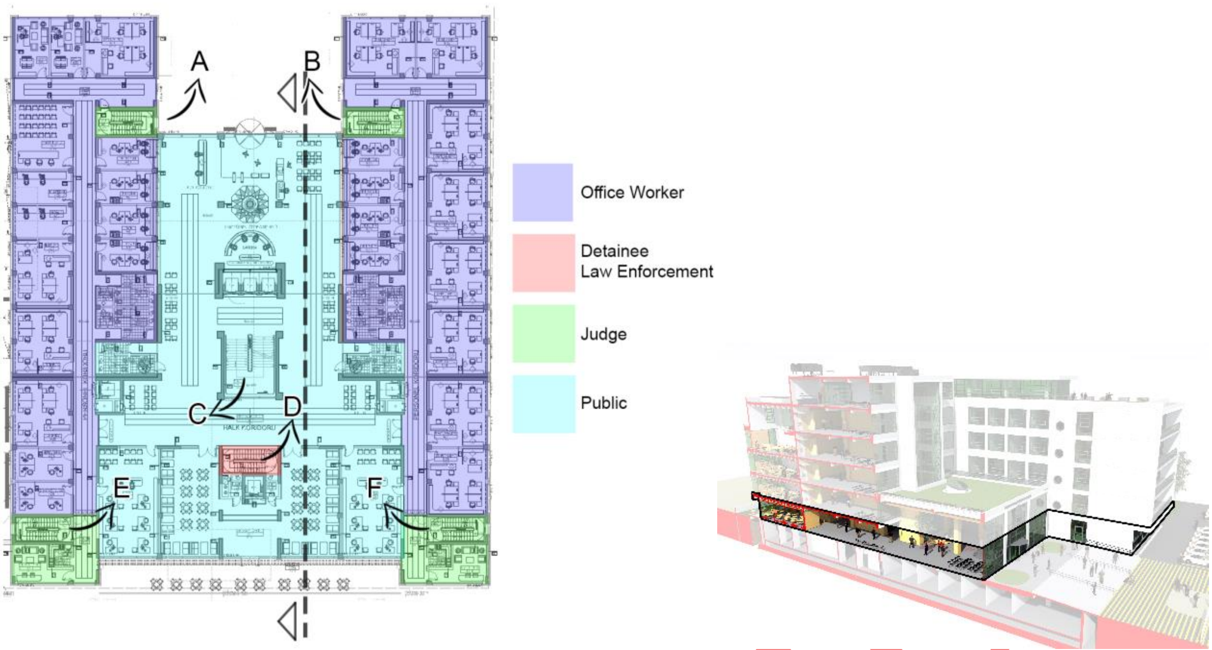

Figure 2. *Ground Floor Plan of the Building*

Stairwells and Exits

The building has six stairwells identified by letter codes (Figure A1):

- **Stairwell D:** Reserved for the descent of detainees, with a width of 125 cm.
- **Stairwells A, B, E, and F:** Emergency staircases, each 125 cm wide.
- **Stairwell C:** The main staircase, 270 cm wide.

The location of these stairwells relative to exits and areas with high pedestrian traffic is critical to understanding potential bottlenecks during an evacuation.

Floor Plans and User Profiles

Figures 2 and A2-A7 show the color-coded floor plans, indicating access restrictions for different user profiles:

- **Purple:** Office worker access.
- **Red:** Detainee and law enforcement access.
- **Green:** Judge access.
- **Turquoise:** Public access.

This color-coding system visually represents the potential flow of different user groups during an evacuation. By meticulously analyzing these architectural features and incorporating access control into the simulation model, a realistic representation of occupant movement patterns during an evacuation is ensured. This detailed analysis is crucial for developing effective strategies to identify potential bottlenecks and improve the building's overall evacuation safety.

Figure A9 illustrates the internal spatial connectivity in the Ordu Annex Courthouse. The diagram is a detailed floor plan overlaid with a network of colored circles and lines representing connections between various areas of the building. Each circle corresponds to specific zones or rooms, with different colors indicating different types of areas. The lines indicate the paths or routes connecting these areas, highlighting critical evacuation routes, corridors, or access points. The network structure emphasizes the relationship between different areas, focusing on how building occupants might move through the building, especially during emergencies.

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4.3. Determining Occupant Load

Accurately determining the building's occupant load is essential for a realistic evacuation simulation. This study uses the widely accepted NFPA 101 standard to calculate the occupant loads of the Ordu Annex Courthouse (NFPA, 2018). NFPA 101 provides specific occupant load factors (area per person) for various space types and accounts for typical usage patterns.

Occupant Load Factors and Calculations

Table 1 summarizes the occupant load factors derived from NFPA 101 for different building use categories. These factors were used to calculate the maximum occupant load for each area.

Table 1. *Occupant Loads According to NFPA 101 [30]*

Use	Permitted Area (m² per person) / Detail
Assembly Areas	
Assembly (Concentrated)	0.65 m² per person (net)
Assembly (Less Dense)	1.4 m² per person (net)
Bank-Type Seating	45.5 cm per person
Fixed Seating	Number of seats
Offices	9.3 m² per person (gross)
Detention Areas	11.1 m² per person (gross)
Storage Areas	46.5 m² per person (gross)

Net and Gross Area: Net area refers to the usable floor space within a room, excluding areas occupied by walls, columns, or fixed furniture. Gross area refers to the total floor area, including unused spaces.

Assembly Areas: The distinction between "concentrated" and "less dense" assembly areas depends on the type of activity and the expected density of people. For example, a courtroom with fixed seating is considered a less dense assembly area compared to a standing-only event.

Table 2 presents the occupant load factors applied to each type of space within the Ordu Annex Courthouse.

Table 2. *Occupant Loads for Courthouse Buildings [30]*

Location	Use	Occupant Load Factor / Detail
Courtroom (Fixed Seating Arrangement)	Assembly (Fixed Seating)	Number of seats
Clerk's Office	Office	9.3 m² per person (gross)
Prosecutor's Office	Office	9.3 m² per person (gross)
Judge's Chamber	Office	9.3 m² per person (gross)
Waiting Area	Assembly	Number of seats (expert estimate)
Cafeteria	Assembly	Number of seats (expert estimate)
Archive	Storage	46.5 m² per person (gross)
Detention Area	Detention	11.1 m² per person (gross)
Kitchen	Kitchen	9.3 m² per person (gross)

Note: For areas without specific NFPA 101 factors (e.g., waiting areas), seat counts were estimated based on typical layouts and design considerations to reflect realistic occupancy.

Table 3 details the calculated occupant loads for each floor and space type in the Ordu Annex Courthouse. The total calculated occupant load for the entire building is 2378 people.

Table 3. *Occupant Load Calculation of the Ordu Annex Courthouse Building*

Floor	Space Type	Area (m²)	Occupant Load Factor (NFPA 101)	Calculated Occupants
Basement	Detention Area	332	11.1 m² per person (gross)	30
	Storage Area	2844	46.5 m² per person (gross)	61
Ground Floor	Cafeteria	224	Number of Seats (Assume 88 seats)	88
	Offices	2674	9.3 m² per person (gross)	288
1st Floor	Courtrooms	370	Number of Seats (Assume 162 seats)	162
	Offices	2360	9.3 m² per person (gross)	254
2nd Floor	Courtrooms	370	Number of Seats (Assume 162 seats)	162
	Offices	2360	9.3 m² per person (gross)	254

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3rd Floor	Courtrooms	370	Number of Seats (Assume 162 seats)	162
	Offices	2360	9.3 m² per person (gross)	254
4th Floor	Courtrooms	80	Number of Seats (Assume 64 seats)	64
	Offices	2320	9.3 m² per person (gross)	249
Roof Terrace	Restaurant	454	Number of Seats (Assume 272 seats)	272
	Kitchen	117	9.3 m² per person (gross)	13
	Offices	606	9.3 m² per person (gross)	65
Total				**2378**

Assumptions: Expert assumptions based on the building's floor plans and descriptions were used to determine the number of seats in courtrooms, the cafeteria, and the restaurant.

Occupant Load Factors: The occupant load factors used are based on the NFPA 101 standard [30] and reflect typical occupancy densities for different types of spaces.

Total Occupant Load: Based on these calculations, the total occupant load of the building is 2378 people.

Space Specific Seat Count Estimations

For areas where the number of seats was estimated:
- **Courtrooms:** A 100% occupancy rate was assumed during peak hours to account for potential variations in daily scheduling and attendance.
- **Cafeteria and Restaurant:** Seating capacity was determined by analyzing typical table and chair arrangements in similar facilities, combined with an estimated comfortable seating density to prevent overcrowding. Peak meal times, which were assumed to coincide with potential evacuation events, were also taken into account.

4.4. Agent-Based Simulation Setup

To model and analyze the evacuation process in the Ordu Courthouse, this study used Pathfinder, a widely recognized microscopic evacuation simulation software [14]. Pathfinder's ability to simulate individual user behaviors, handle complex building layouts, and produce user-friendly visual outputs makes it suitable for this research.

Building Model and Occupant Placement

The architectural drawings of the courthouse (Figures 2, A2-A7) were imported into Pathfinder to create a detailed model that replicates the walls, corridors, stairs, exits, and other architectural elements affecting pedestrian flow. The calculated occupant loads (Table 3) were carefully assigned to the corresponding areas in the model.

Occupant Profiles

Four different occupant profiles were defined to enhance the realism of the simulation: detainees, judges, office workers, and the public. Considering the diverse demographics of courthouse occupants, each profile was assigned ranges of walking speeds. Judges, office workers, and the public shared a common walking speed distribution, while law enforcement officers were assigned a 10% faster distribution to reflect their potential for greater mobility during emergencies. Detainees were assigned a 13% slower walking speed distribution based on studies indicating increased energy expenditure and naturally lower preferred walking speeds for individuals with restricted arm movement (handcuffed) [35, 36]. Figure 3 shows the walking speed distributions assigned to each occupant profile.

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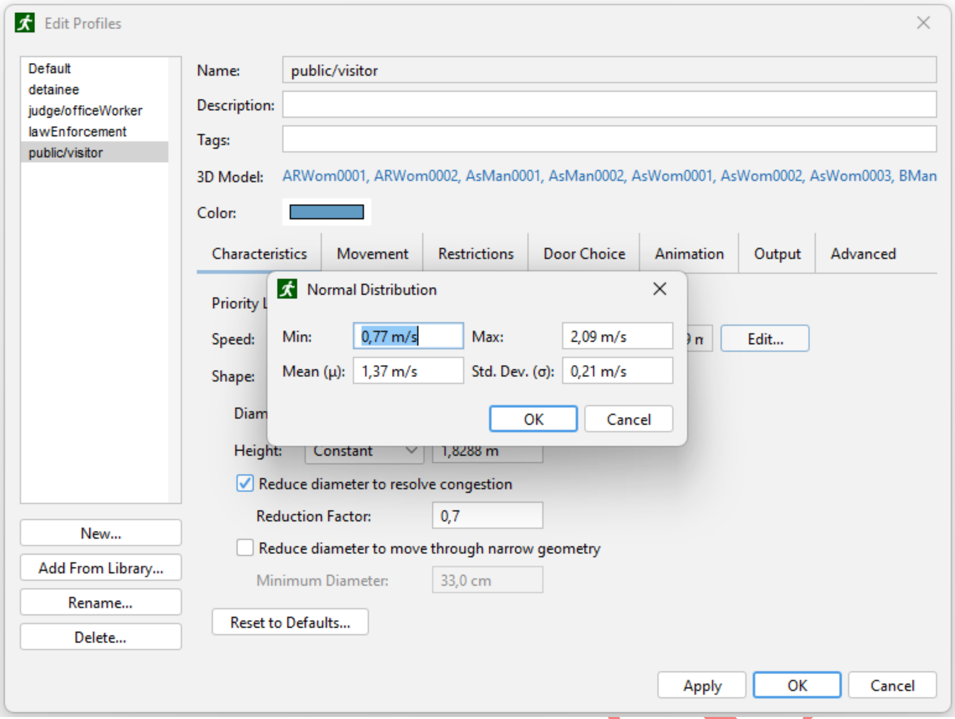

***Figure 3.** Occupant Profile Settings in the Agent-Based Model (ABM)*

Simulation Parameters

Realistic evacuation parameters, derived from the literature, observations, and established pedestrian behavior models, were defined in Pathfinder to govern occupant movements and decision-making processes:

- **Maximum Walking Speeds:** To reflect varying mobility [23], three distinct maximum walking speed distributions were assigned to different occupant profiles:
    - **Normal:** Assigned to the public, office workers, and judges. (Minimum: 0.77 m/s, Maximum: 2.09 m/s, Mean: 1.37 m/s, Standard Deviation: 0.21)
    - **Slow:** Assigned to detainees, simulating restricted arm movement (13% slower than the "Normal" distribution, reflecting findings from [35, 36]).
    - **Fast:** Assigned to law enforcement officers, reflecting their potential for greater mobility in emergencies (10% faster than the "Normal" distribution).
- **Desired Walking Speeds:** To simulate the effects of urgency and crowd density on movement, desired speeds (speeds that individuals aim to achieve) were dynamically modeled within Pathfinder [8]. These speeds ranged from 0 m/s to the maximum walking speed assigned to each individual.
- **Collision Avoidance:** Realistic collision avoidance settings were implemented based on typical pedestrian interactions and personal space considerations.
- **Exit Selection Rules:** Occupant exit selection was modeled based on accessibility to specific sections, proximity, perceived congestion levels, and distance to safe locations [34].

4.5. Scenario Analysis

The simulation environment was meticulously designed to mirror the real-world use and security protocols of the Ordu Annex Courthouse, including replicating access control measures and restricting movement between different building sections. At the start of the simulation:

- **Detainees:** Remained stationary until a law enforcement officer arrived to escort them to the detainee vehicle at the basement exit (Figure A10).
- **Other Occupant Groups:** Were directed by the simulation to the nearest/fastest exit, passing through sections according to their access levels, reflecting realistic evacuation behavior.

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By accurately modeling these procedural constraints, the simulation provides a realistic assessment of how different groups would navigate the courthouse during an evacuation. This detailed scenario setup ensures a comprehensive analysis of evacuation dynamics, taking into account the access restrictions and movement patterns of various occupant groups.

4.6. Model Validation

To enhance the reliability and realism of the simulation model, a face validation process was conducted with three subject matter experts:

- **Architect (Expert 1):** Over 10 years of experience in courthouse design, including expertise in evacuation planning and accessibility.
- **Fire Safety Engineer (Expert 2):** Professional Engineer (PE) license, specializing in fire safety design and evacuation modeling for large buildings.
- **Security Consultant (Expert 3):** Experienced in courthouse security assessments and the development of security protocols and procedures.

The experts were provided access to the Pathfinder model, including building geometry, occupant placement, and selected evacuation parameters. Feedback was collected on the following key aspects:

- **Realism of Occupant Placement:** Expert 1 verified the occupant distribution within courtrooms, offices (based on typical desk layouts), and public areas (considering peak-hour usage). Expert 2 suggested a minor adjustment to the cafeteria seating arrangement to better reflect typical dining layouts, which was incorporated into the model.
- **Appropriateness of Walking Speeds:** Expert 2 reviewed the literature-based walking speed distributions and concurred with the ranges chosen.

5. RESULTS

This section presents the key findings obtained from the Pathfinder simulations of the Ordu Annex Courthouse evacuation. By analyzing data on evacuation times, congestion levels, and travel distances, potential bottlenecks in the building's evacuation routes are identified.

5.1. Overall Evacuation Time and Congestion

Pathfinder simulations revealed a wide range of evacuation times for occupants, ranging from 1 to 366 seconds (Figure 4).

- **95th Percentile:** 95% of the occupants were able to evacuate within 316 seconds. This suggests that the majority experienced a relatively efficient evacuation process.
- **Remaining 5%:** The slowest 5% of occupants (117 individuals) required an additional 50 seconds to complete the evacuation. This highlights the presence of potential bottlenecks affecting this group. Of this group, 38 were from the public profile, while 79 were from the judge/office worker profiles.

Congestion times, defined as the time individuals moved at speeds lower than 0.25 m/s throughout the evacuation, also varied significantly, ranging from 0 to 202 seconds (Figure 4).

- **95th Percentile:** The top 5% (the 5% with the longest congestion time) experienced prolonged congestion times exceeding 153 seconds, highlighting areas where pedestrian flow was significantly restricted.
- **Overlap:** Notably, 59 individuals within the slowest 5% in terms of total evacuation time also belonged to the group experiencing the longest congestion times. This indicates a correlation between congestion and overall evacuation efficiency.

Occupant travel distance, defined as the distance an occupant traveled during the simulation, ranged from 0.5 m to 218.5 m (Figure 4).

- **95th Percentile:** The 95th percentile of the occupants' travel distance was less than 155.8 meters. The other 5% experienced significantly longer travel distances.

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- **Overlap:** Interestingly, while the 5% group with the longest travel distance did not significantly overlap with those experiencing the most congestion (only one person in common between these two groups), there was a significant overlap between occupants who traveled the longest distances and those with the longest evacuation times. This suggests that the length of the path to the exit significantly affects the overall evacuation time, but not necessarily the level of congestion experienced (Figure 5 illustrates the organizational relationship between these three parameters of evacuation).

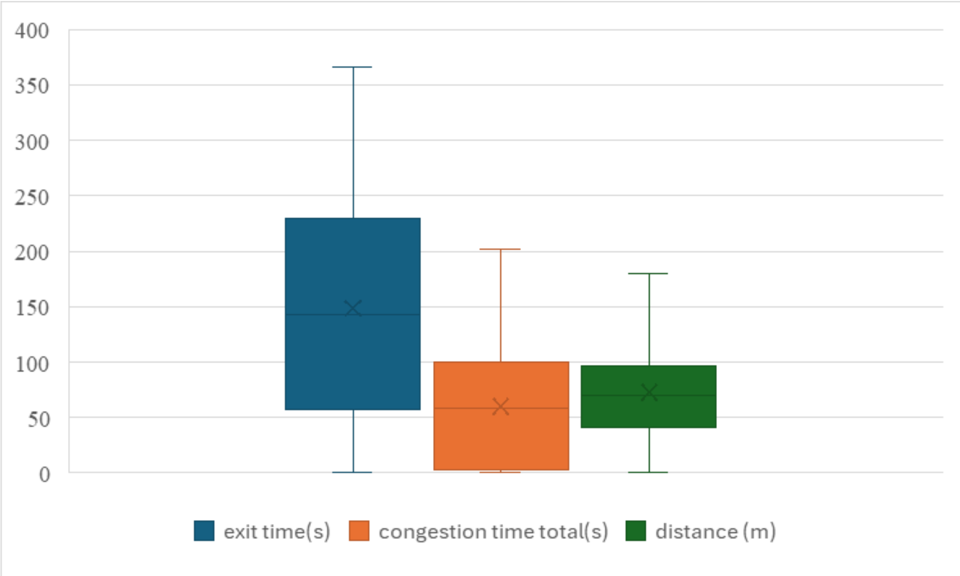

Figure 4. *Total Evacuation Time, Average Congestion Time and Average Travel Distance of Occupants*

Figure 5. *The Relationship Between Evacuation Time, Congestion Time and Travel Distance*

5.2. Occupant Profile Analysis

Analysis of evacuation metrics by occupant profile reveals significant differences:

- **Exit Times:** The public and judge/office worker profiles showed similar exit time distributions, with medians around 150 seconds. In contrast, the detainee and law enforcement profiles had significantly shorter median exit times (around 90 seconds), likely due to their dedicated circulation paths and escort procedures (Figure 6).

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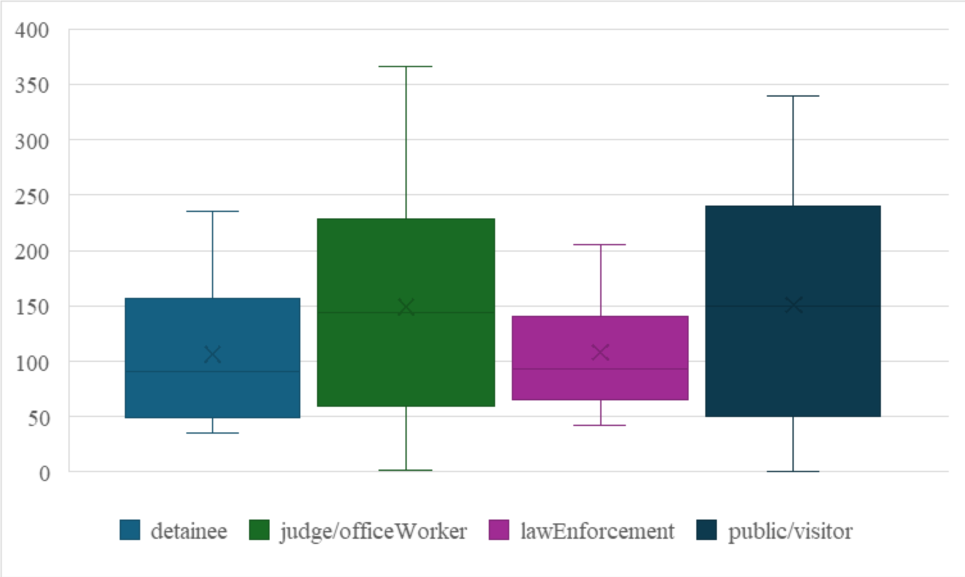

Figure 6. *Exit Time by Occupant Profile*

- **Congestion Times:** Similar to exit times, congestion times for the public and judge/office worker profiles were comparable. Interestingly, law enforcement officers experienced longer congestion times than detainees (Figure 7). This could be attributed to the fact that law enforcement officers do not experience congestion when alone but encounter congestion in narrow areas while escorting detainees.

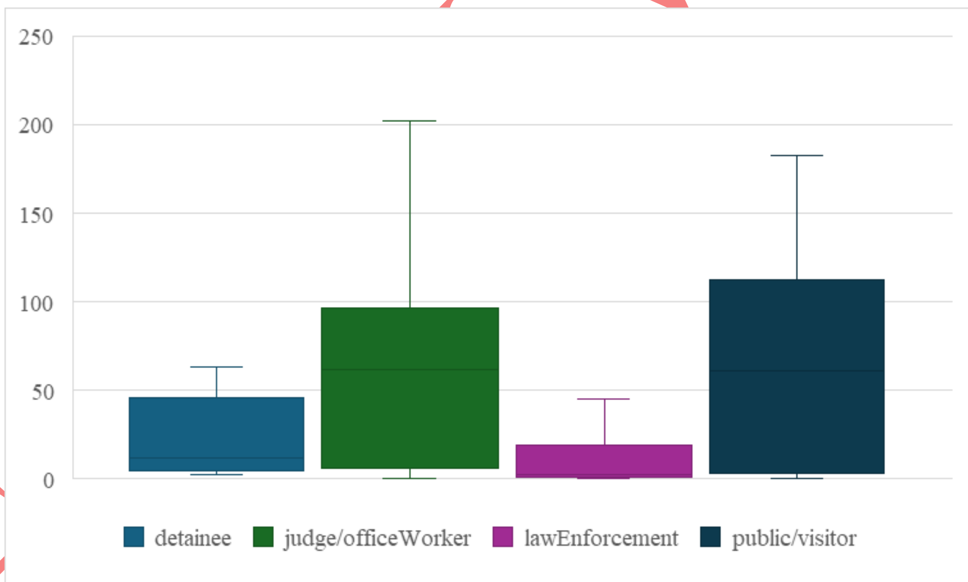

Figure 7. *Congestion Time by Occupant Profile*

- **Travel Distance:** Law enforcement officers had the longest median travel distance, primarily due to their responsibility to reach detainees and escort them to the detainee vehicle in the basement. The public group had to travel a longer distance than other groups, as they could only use the main staircase (Stair C), which was more than 20 m from the nearest exit (Figure 8).

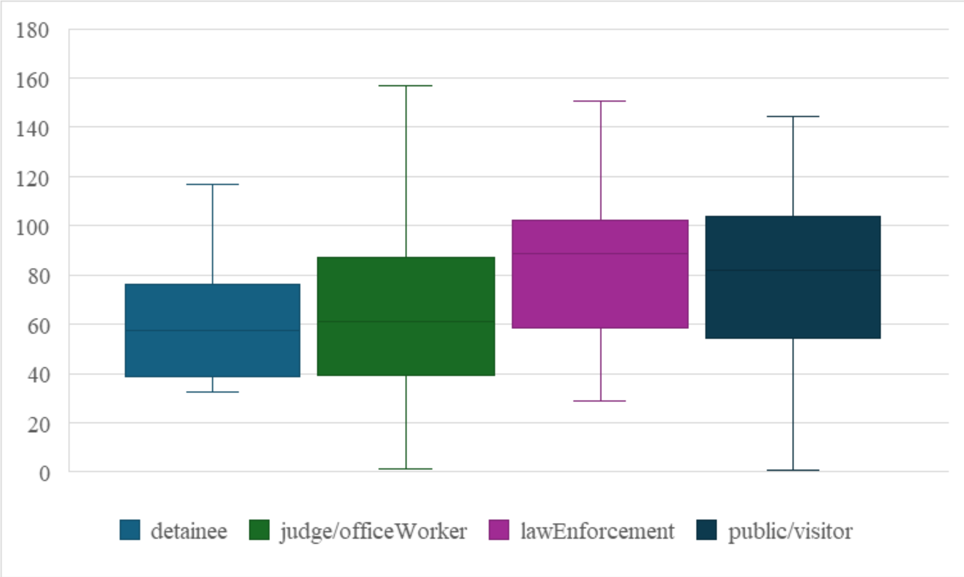

Figure 8. *Distance Travelled to Exit by Occupant Profile*

These findings underscore the importance of considering occupant profile-specific movement patterns and restrictions when analyzing evacuation performance and designing optimization strategies.

5.3. Visual Analysis of Bottlenecks

This section examines the bottleneck results through a comprehensive visual analysis. Flow charts and congestion graphs were used to depict the movement patterns of occupants throughout the evacuation process and to highlight areas of congestion.

Flow Rate Analysis of Stairs

Analysis of the flow rate at the stairwells, which are critical components of the evacuation routes, revealed significant differences in capacity (Figure 9, Figures C1-2). In flow rate graphs, bottleneck formation is often characterized by flow rates reaching a plateau, indicating that a section is operating at or near its maximum capacity.

- **Basement to Ground Floor:** As anticipated, due to the relatively low occupant load in the basement, no stairwell reached capacity on this route (Figure 9, left).
- **Ground Floor to First Floor:** Stair D, reserved for detainees, was significantly underutilized (Figure 9, right). Stair B also saw limited use and was empty after the 230-second mark. Stairs F, A, C, and E followed Stair B in that order.
- **Upper Floors:** A similar pattern emerged on the upper floors. Stair B and D were generally less congested, while the main staircase, Stair C, briefly reached its highest capacity around the 200-second mark, indicating a potential for congestion during peak evacuation periods (Figures C1-C2).

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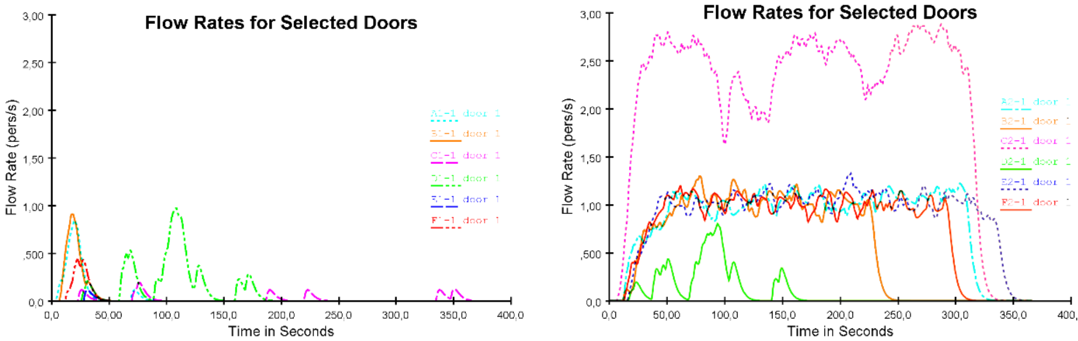

Figure 9. *Flow Rates at Stairwells (basement-to-ground (left) and ground-to-first floor staircases (right))*

Queue Formation and Congestion Patterns

Queue formation graphs are used to investigate congestion points in the building. Queue formation graphs are presented in Figure 10 (plan view) and Figure 11 (perspective view), where red areas indicate congested areas.

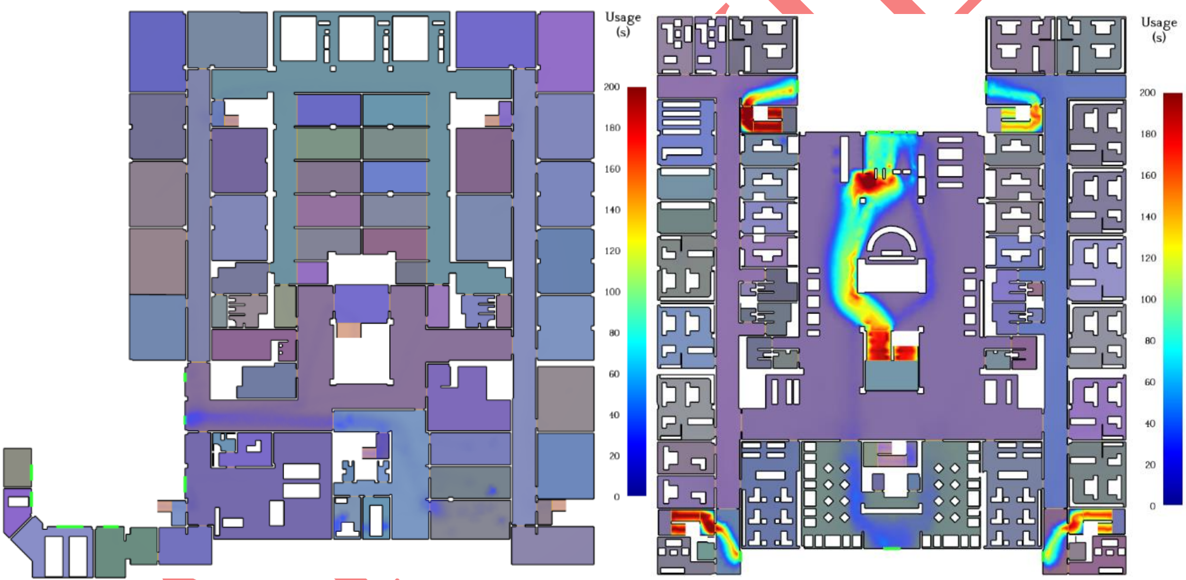

Figure 10. *Congestion Heat Maps for the Basement Floor (Left) and Ground Floor (Right)*

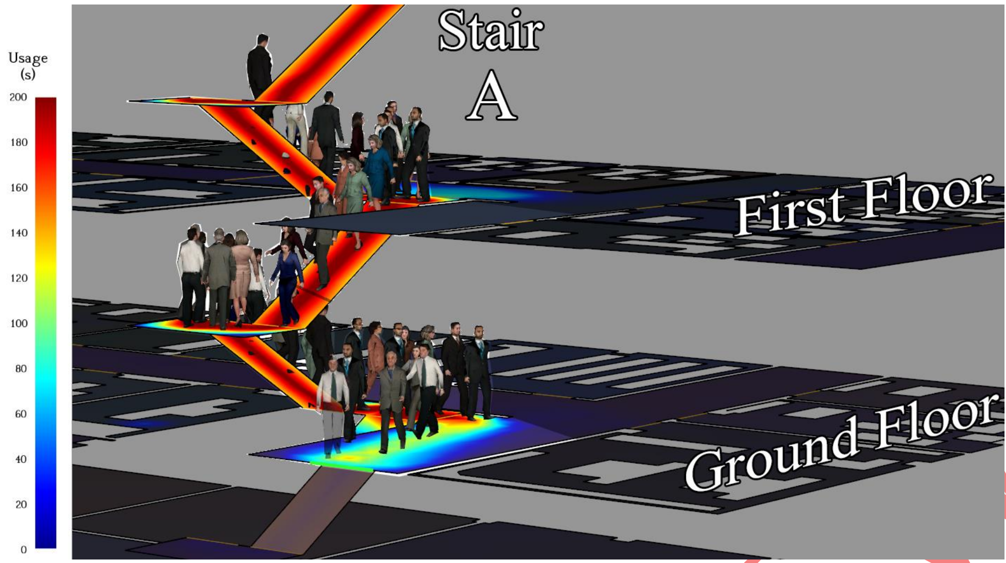

Figure 11. *Simulation Snapshot of Pedestrian Flow*

- **Basement Floor:** As expected, no significant congestion was observed in the basement due to the low user load (Figure 10, left).
- **Ground Floor:** The highest density was experienced at Stair A, followed by Stairs E, F, and B (Figure 10, right).
- **Upper Floors:** Congestion patterns on the upper floors were similar to the ground floor, with Stairs A and E experiencing higher densities. Interestingly, on the fourth floor, occupants descending from the fifth-floor dining hall (inaccessible via Stairs A, B, and D) initially congested Stair C but later diverted to the less congested Stair A, indicating dynamic route selection behavior in response to congestion (Figures B1-B3).

Sensitivity Analysis Findings

The sensitivity analysis was performed by modifying two critical parameters: occupant load and walking speed. The results, presented in Table 4, show how these changes affect evacuation time.

- **Effect of Occupant Load on Evacuation Time:** As the occupant load increased from 80% to 120%, there was a noticeable increase in evacuation time. Specifically:
  - At 80% occupant load, the evacuation time was 305 seconds (83%).
  - Increasing the load to 90% resulted in an evacuation time of 326 seconds (89%).
  - The standard occupant load (100%) resulted in an evacuation time of 366 seconds.
  - At 110%, the evacuation time increased to 382 seconds (104%).
  - Finally, when the occupant load reached 120%, the evacuation time was 406 seconds (111%).

These results indicate a near-linear relationship between occupant load and evacuation time, suggesting that as the building becomes more crowded, the time required for evacuation increases significantly. When the occupant load is increased or decreased by a certain rate, the evacuation time changes at a lower rate than this rate of increase. The reason behind this could be attributed to people being able to choose alternative routes when the number of occupants increases. In the case of reduced occupant load, it may be due to the inability to shorten the evacuation time because of existing bottlenecks in the building.

- **Effect of Walking Speed on Evacuation Time:** The sensitivity analysis also explored the impact of altering the walking speed of occupants (Table 4):
  - When the walking speed was reduced to 80%, the evacuation time increased significantly to 435 seconds (119%).
  - At 90% of the standard walking speed, the evacuation time decreased to 395 seconds (108%).

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- With the standard walking speed (100%), the evacuation time was calculated as 366 seconds.
- Increasing the walking speed to 110% reduced the evacuation time to 336 seconds (92%).
- At 120% of the standard walking speed, the evacuation time was observed to decrease to 324 seconds (89%).

These results demonstrate that walking speed has a significant impact on evacuation time. Faster walking speeds lead to quicker evacuations, while slower speeds significantly extend the time required to clear the building. There is an inverse linear relationship between walking speed and evacuation time, but the effect of increasing walking speed on evacuation time diminishes after a certain point. This is because in densely populated buildings, bottlenecks cause congestion, preventing people from reaching the exits at their maximum walking speeds.

Table 4. *Sensitivity Analysis Findings.*

	Evacuation Time (s)				
	80%	**90%**	**100%**	**110%**	**120%**
Occupant Load	305	326	366	382	406
	83%	89%	100%	104%	111%
Walking Speed	435	395	366	336	324
	119%	108%	100%	92%	89%

The sensitivity analysis underscores the importance of both occupant load and walking speed in evacuation scenarios. Increasing the occupant load leads to longer evacuation times, while increasing walking speed can mitigate some of these delays (Figure 12). These findings highlight the need for careful management of building occupancy levels and consideration of factors that may hinder walking speed, such as obstacles or physical limitations of the occupants. By optimizing these parameters, it may be possible to improve evacuation efficiency and enhance overall safety during emergencies.

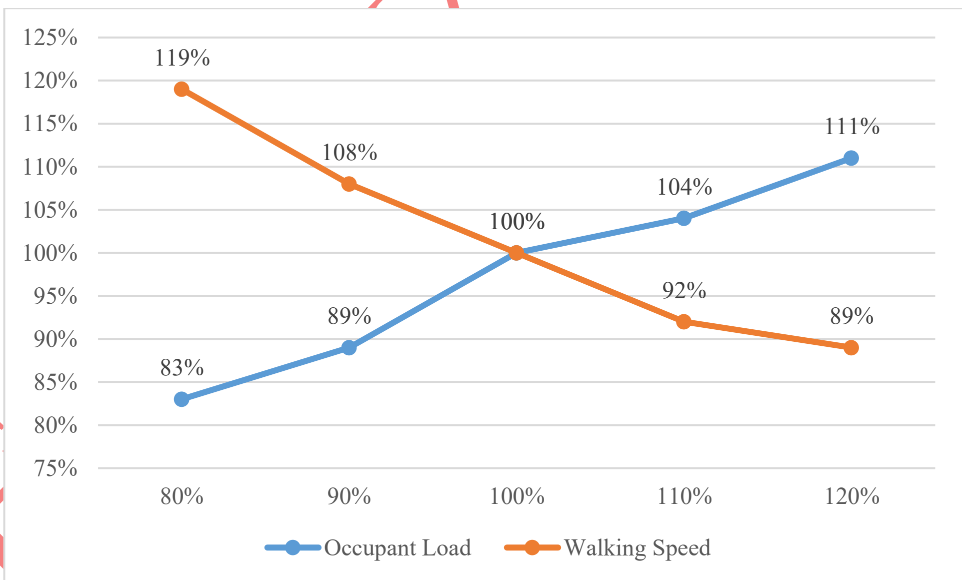

Figure 12. *Sensitivity Analysis Findings*

6. DISCUSSIONS

6.1. Overall Evacuation Time

Evacuation time is a critical metric for evaluating the effectiveness of emergency procedures in complex, densely populated buildings like the Ordu Annex Courthouse. The Pathfinder simulations revealed that evacuation times for occupants ranged from 1 to 366 seconds. The 95th percentile evacuation time was 316 seconds, meaning that 95% of the occupants were evacuated within this time frame. This aligns closely with international safety recommendations for densely populated buildings, which generally aim for evacuation times of 300 seconds or less [37].

However, the remaining 5% of occupants, particularly those categorized under the public and judge/office worker profiles, experienced significantly longer evacuation times, reaching up to 366 seconds. This discrepancy indicates potential bottlenecks or congestion points that delay evacuation for specific groups, a well-documented issue in emergency evacuation studies where bottlenecks can severely impact evacuation efficiency [8].

Congestion times, where occupants' movement speed fell below 0.25 m/s, ranged from 0 to 202 seconds, with the most affected individuals (the top 5%) experiencing congestion times exceeding 153 seconds. The literature suggests that such high levels of congestion can not only delay evacuation but also increase the risk of accidents and panic [7]. Approximately half of the occupants in the top 5% in terms of evacuation time also experienced prolonged congestion, indicating a direct correlation between these delays and bottleneck formation.

Travel distance, another important factor, varied greatly from 0.5 to 218.5 meters. It was noteworthy that while those with the longest travel distances did not always experience the worst congestion, there was a significant overlap between the longest travel distances and the longest evacuation times, suggesting that building layout and exit placement play a crucial role in evacuation delays. Research has shown that optimizing travel routes and minimizing the distance to exits can significantly reduce overall evacuation times [38].

In summary, while the overall evacuation time for most occupants was within acceptable limits, targeted improvements such as addressing bottlenecks and optimizing exit routes in the courthouse design are necessary to ensure that even the slowest occupants can evacuate safely. This aligns with findings in evacuation research that emphasize addressing congestion points and travel distances to enhance evacuation efficiency [39].

6.2. Evacuation Performance of the Occupant Profiles

The evacuation performance of different occupant profiles in the Ordu Courthouse varied significantly, reflecting differences in mobility, access to exits, and designated routes.

The public and judge/office worker profiles had similar median evacuation times, approximately 150 seconds. Both groups faced common bottlenecks, resulting in prolonged congestion times. Previous research highlights that shared exit routes in high-density environments can significantly slow down evacuation [15]. Reducing congestion through design interventions such as wider corridors or additional exits can improve evacuation efficiency [9].

Detainees and law enforcement officers had shorter average evacuation times (approximately 90 seconds) due to dedicated routes, minimizing congestion. However, law enforcement officers experienced slightly longer congestion times, likely due to escorting detainees. Law enforcement officers can experience counter-flow during evacuations. This highlights the importance of clear, unobstructed paths for security personnel during evacuations [5].

6.3. Implications for Courthouse Design

These performance differences indicate that the public and office worker groups need optimized exit strategies to reduce congestion, while maintaining dedicated routes for detainees and law enforcement ensures a quick evacuation. These findings align with best practices in evacuation planning, highlighting the need for tailored strategies for different groups [7].

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6.4. Implications for Courthouse Design

A rigorous validation process involving visual inspection, expert feedback, and sensitivity analysis was conducted to ensure the accuracy and reliability of the evacuation model for the Ordu Annex Courthouse. This multifaceted approach aimed to confirm that the simulation results closely reflected real-world evacuation dynamics.

Expert Feedback

Expert validation was an integral part of refining the model. Feedback was gathered from professionals specializing in courthouse design, fire safety, and security protocols. These experts reviewed the simulation setup, including occupant placement, walking speed parameters, and exit selection rules. Their feedback led to adjustments in the model, such as seating arrangements and walking speeds, ensuring the simulation accurately reflected real evacuation scenarios [8].

Sensitivity Analysis

A sensitivity analysis was conducted to test the model's robustness under varying conditions. Key parameters such as occupant load and walking speed were adjusted by ±10%. The results showed a near-linear relationship between increased occupant load and extended evacuation times, consistent with existing evacuation research [38]. Similarly, faster walking speeds led to shorter evacuation times, emphasizing the importance of optimizing mobility in emergencies.

Overall, the combination of visual inspection, expert feedback, and sensitivity analysis confirms the validity of the model. This comprehensive approach enhances the credibility of the findings and ensures that the proposed design interventions are based on realistic evacuation dynamics.

7. CONCLUSION

This study provides a detailed analysis of the evacuation performance of the Ordu Annex Courthouse, focusing on identifying and mitigating bottlenecks in evacuation routes. Using Pathfinder simulations, critical areas where congestion hinders efficient evacuation were identified. The analysis revealed that 95% of building occupants could evacuate within 316 seconds, but the remaining 5% experienced significant delays, particularly due to bottlenecks in stairwells.

This study highlights the significant differences in evacuation performance among various occupant profiles in the Ordu Courthouse, influenced by mobility, exit access, and designated routes. While the public and judge/office worker profiles exhibited similar evacuation times and congestion patterns, detainees and law enforcement officers had shorter evacuation times due to dedicated circulation paths. However, law enforcement officers experienced longer congestion periods when escorting detainees through narrow areas. Additionally, the public group covered the longest travel distance due to limited exit options. These results emphasize the need to consider occupant-specific movement patterns when designing evacuation strategies. Implementing design interventions such as improved exit access, minimizing counterflow in constrained spaces, and ensuring clear evacuation paths for security personnel can significantly enhance overall evacuation efficiency.

Supported by visual inspection and expert validation, the results highlighted specific areas where improvements can be made. By addressing these bottlenecks through architectural adjustments such as widening corridors, reconfiguring exits, and strategically placing flow control elements, the overall evacuation efficiency can be significantly improved. The sensitivity analysis further underscored the impact of occupant load and walking speed on evacuation times, suggesting that building capacity and mobility factors must be carefully managed. These findings provide practical insights for architects and building managers, especially for enhancing the safety and resilience of public buildings with high occupancy rates, such as courthouses.

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Future Research Directions

While this study provides valuable insights into the evacuation dynamics of courthouses, several areas warrant further investigation to enhance evacuation strategies. A key avenue for future research is the development and implementation of real-time monitoring systems. Such systems could track occupant movements and congestion during emergencies, enabling dynamic adjustments to evacuation routes in real-time. This approach could help minimize delays and bottlenecks, thereby improving overall evacuation efficiency.

In addition to technical advancements, understanding human behavior in high-stress environments remains critical. Future studies should explore how stress, confusion, or panic affect movement patterns and decision-making during evacuations. Insights from behavioral research can inform evacuation plans that are more aligned with human factors, making them more effective in practice. Similarly, the needs of vulnerable populations, such as individuals with disabilities, elderly occupants, and those unfamiliar with the building, require further attention. Investigating tailored evacuation strategies for these groups can ensure that all occupants can evacuate safely and efficiently.

Courthouses present unique security challenges, and future research should also focus on integrating security protocols into evacuation planning. This includes understanding how the movement of detainees and controlled access areas affect evacuation efficiency. Balancing the need for security with the need for safe evacuation in such environments is critical. Additionally, there is a need for further research to optimize architectural design. Elements such as stairwell configuration, exit placement, and corridor widths can be adjusted to improve occupant flow and reduce congestion.

Finally, the role of evacuation drills and training should not be overlooked. Future studies could examine the impact of regular evacuation drills on staff preparedness and evacuation outcomes. Assessing how well training translates into real-world evacuations will be important for developing comprehensive strategies to enhance courthouse safety. By addressing these research areas, future studies can contribute to more effective and resilient evacuation protocols for courthouses and similar high-occupancy buildings.

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CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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Appendix A: Architectural Plans and Visualizations

Appendix A provides supplementary visual materials to support the analysis presented in the main body of the article. It includes detailed architectural plans of the Ordu Annex Courthouse and highlights the locations of stairwells and access restrictions for different user profiles.

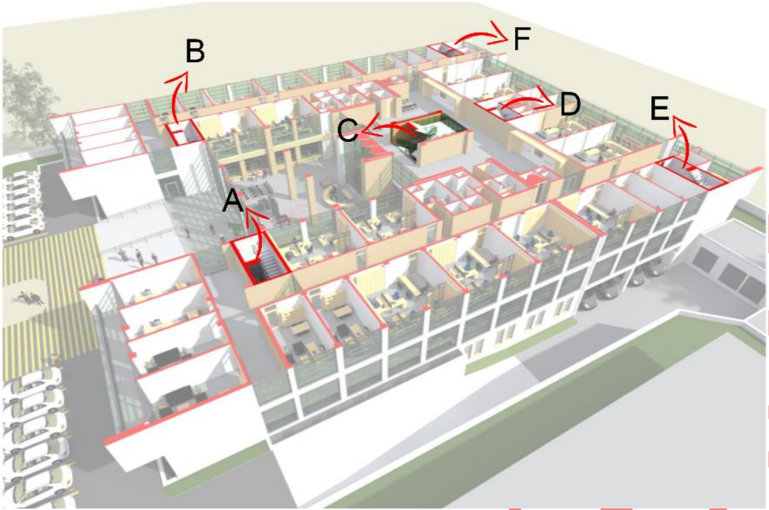

Figure A1. *Floor Plan Perspective of the Building (Courtesy of AYT PROJE)*

Figure A1 provides a comprehensive overview of the Ordu Annex Courthouse's layout, with each stairwell clearly labeled with its corresponding letter code (A, B, C, D, E, F).

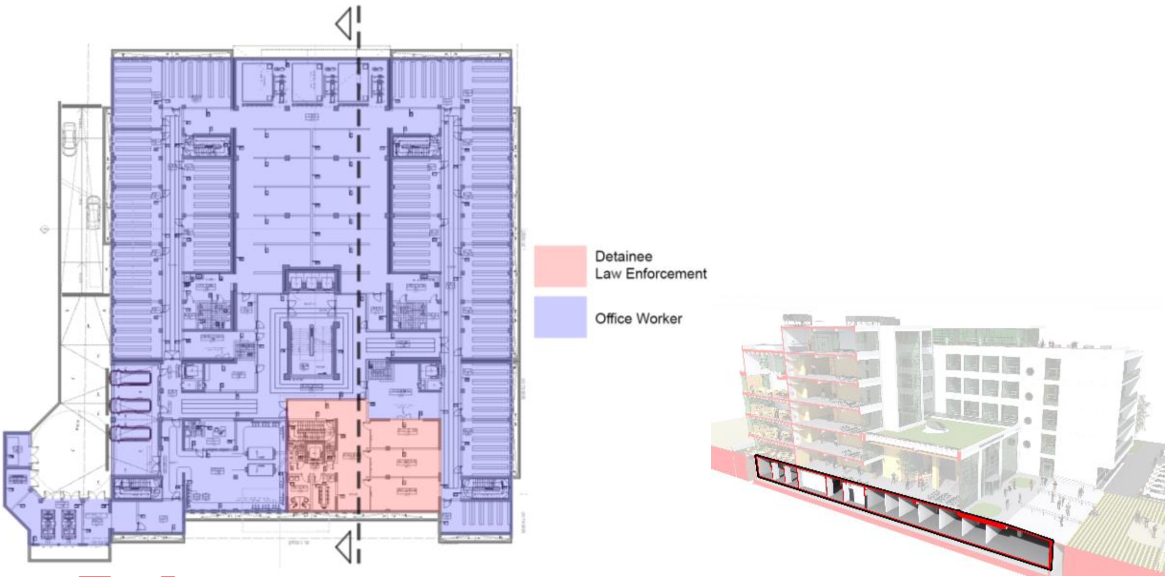

Figure A2. *Basement Floor Plan of the Building (Courtesy of AYT PROJE)*

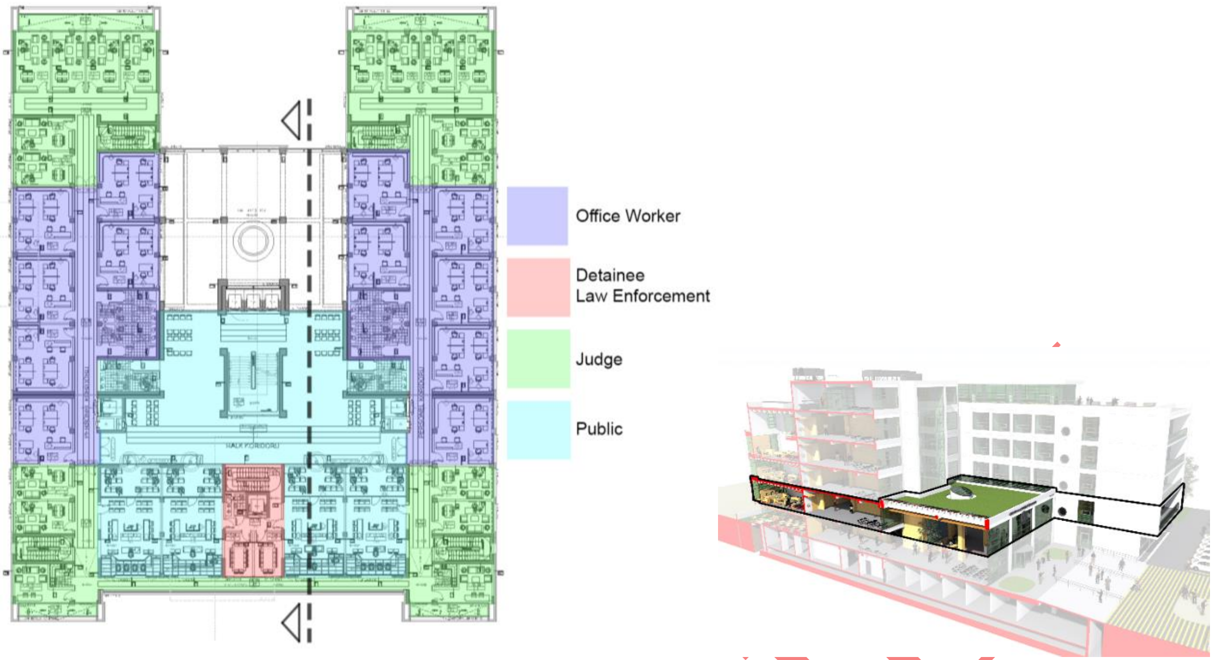

Figure A3. *First Floor Plan of the Building (Courtesy of AYT PROJE)*

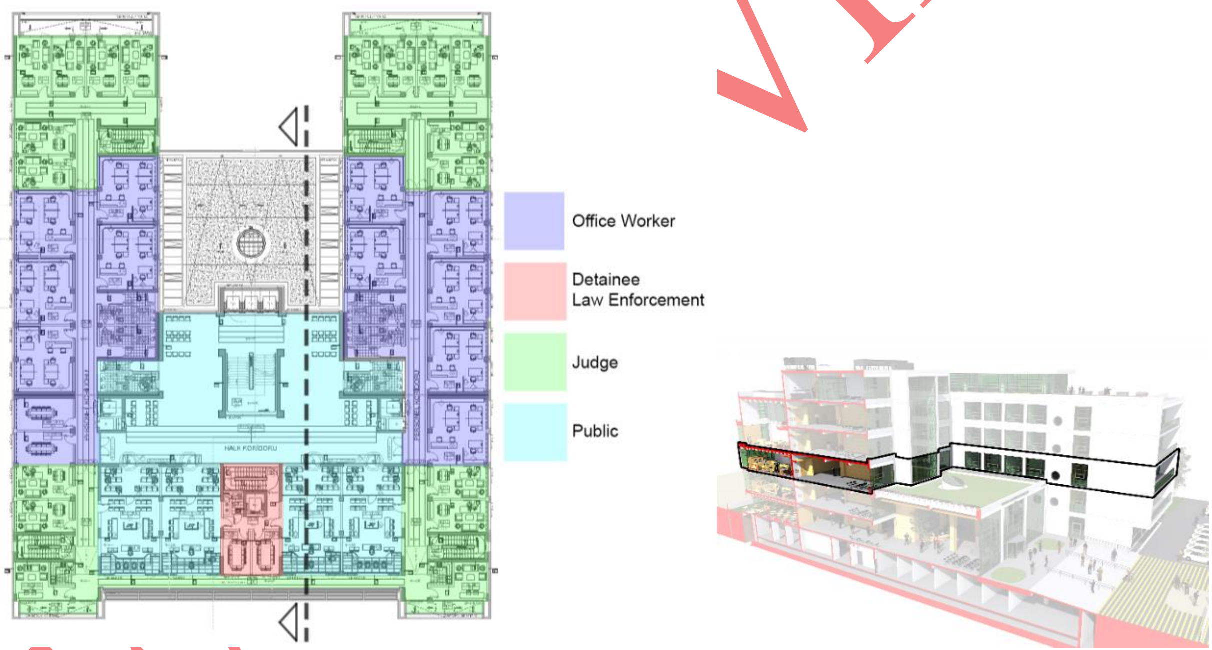

Figure A4. *Second Floor Plan of the Building (Courtesy of AYT PROJE)*

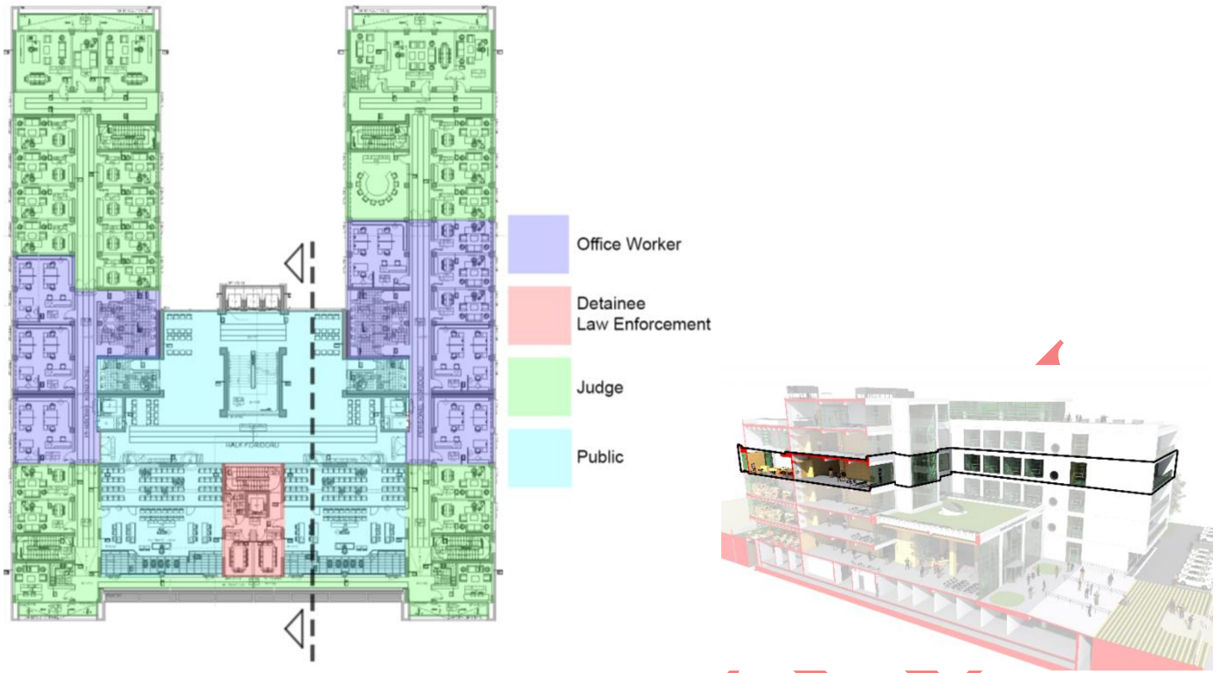

Figure A5. *Third Floor Plan of the Building (Courtesy of AYT PROJE)*

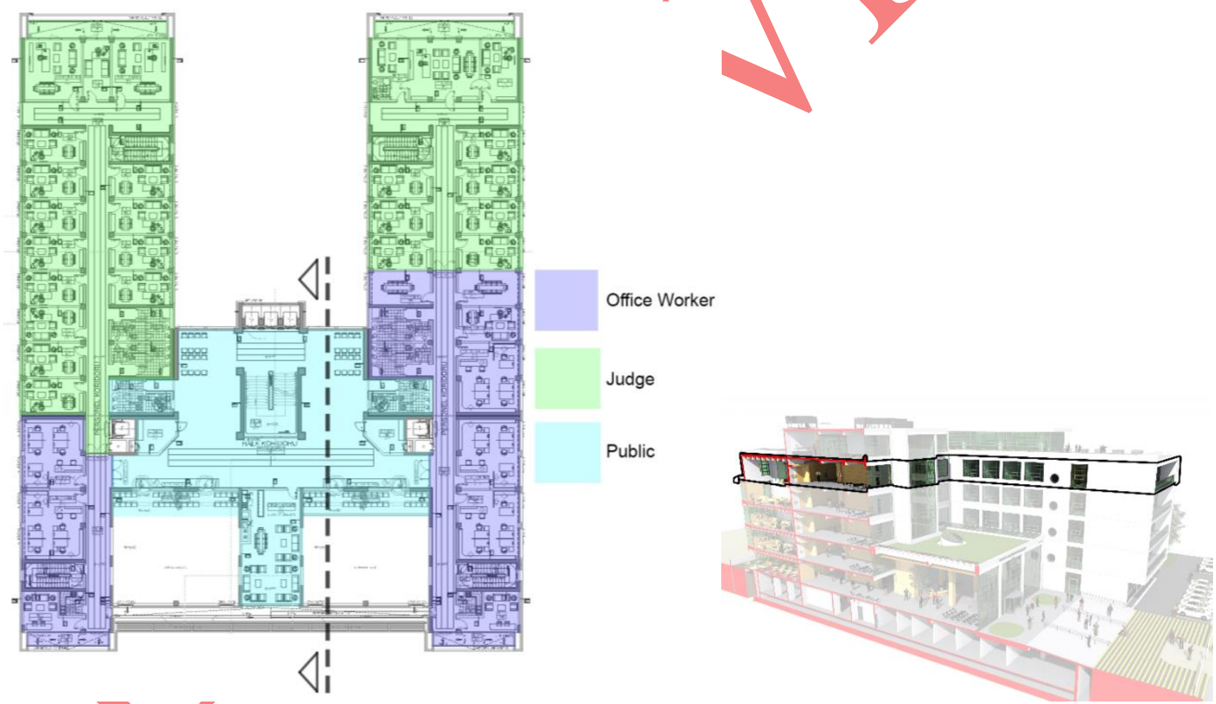

Figure A6. *Fourth Floor Plan of the Building (Courtesy of AYT PROJE)*

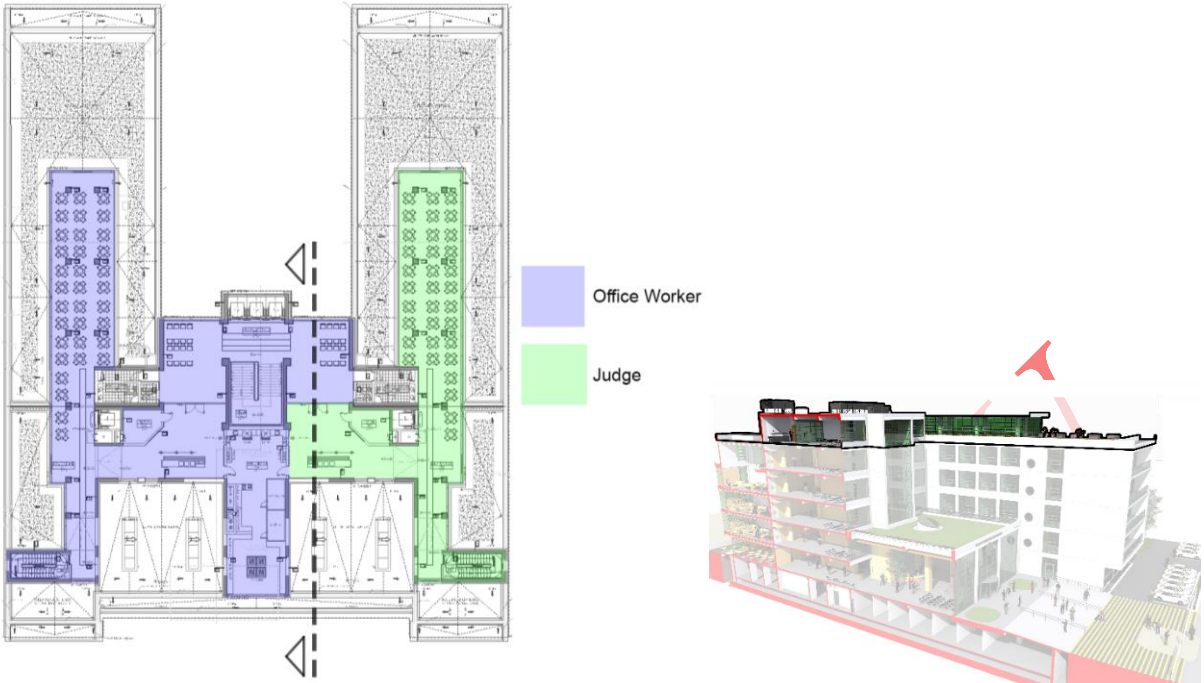

Figure A7. *Roof Terrace (Fifth Floor) Plan of the Building (Courtesy of AYT PROJE)*

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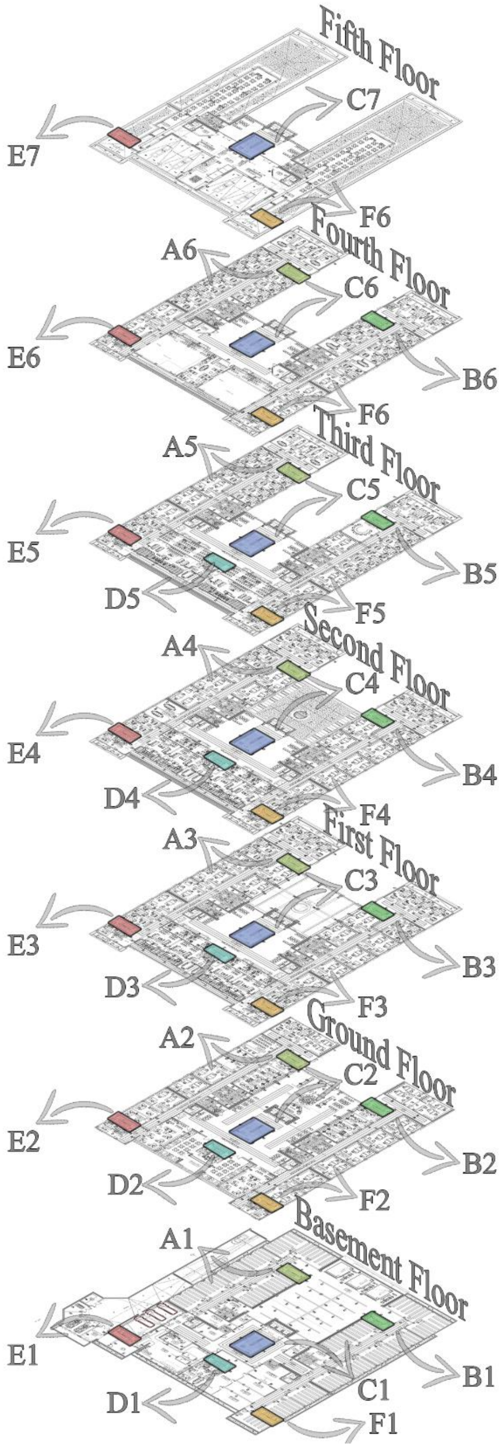

Figure A8. *Stairwell Codes*

EARLY VIEW

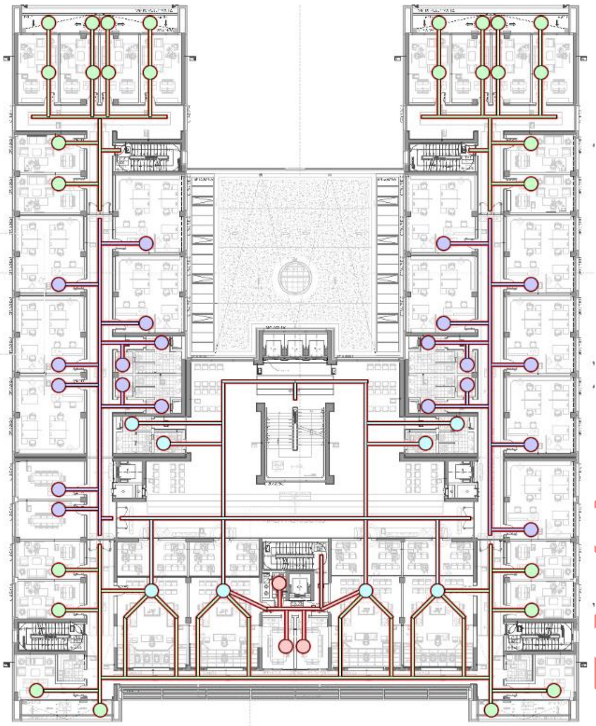

Figure A9. *Network Structure Showing the Relationship Between Different Areas in the Building*

Figure A10. *Law Enforcement Assisting Detainee*

EARLY VIEW

Appendix B: Simulation Visualizations (Congested Areas)

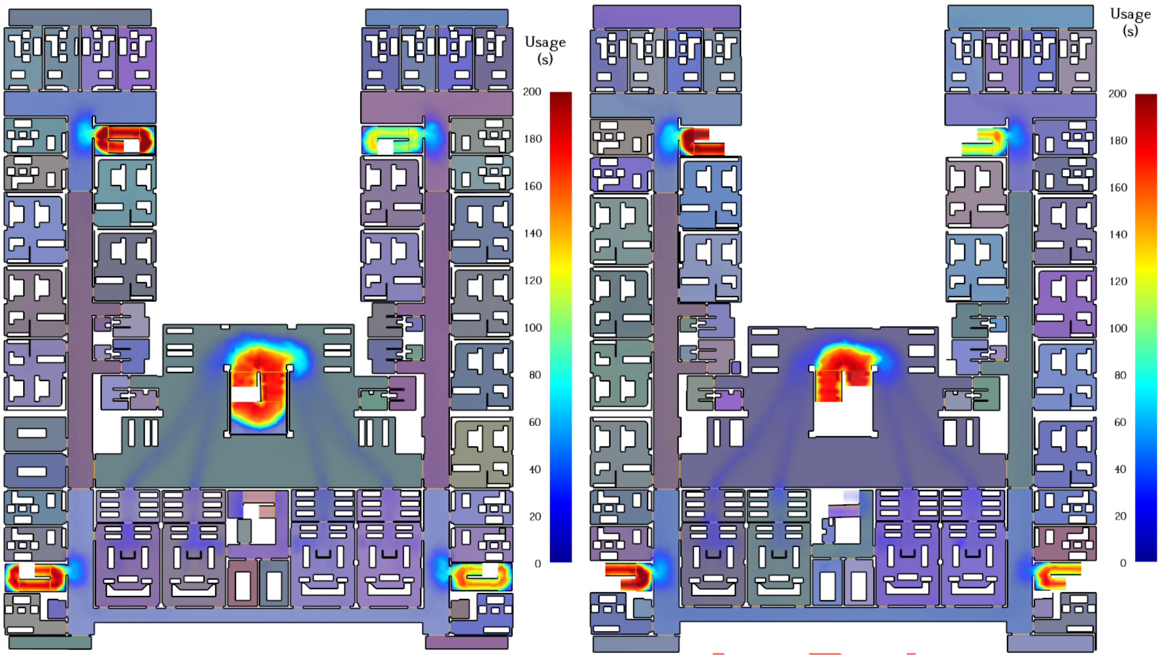

Figure B1. *Congested Areas on the First Floor (left) and Second Floor (right)*

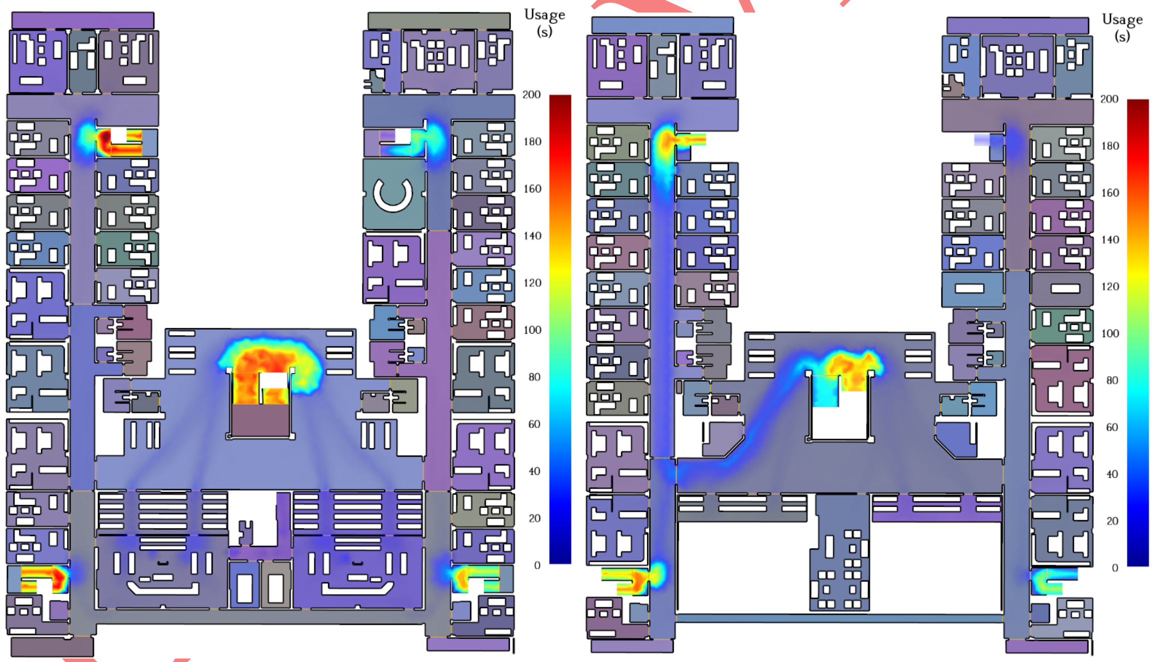

Figure B2. *Congested Areas on the Third Floor (left) and the Fourth Floor (right)*

These heat maps show the congestion levels on the third (left) and fourth (right) floors. Examining congestion patterns across different floor levels helps identify consistent bottleneck locations and assess the overall flow of occupants within the building.

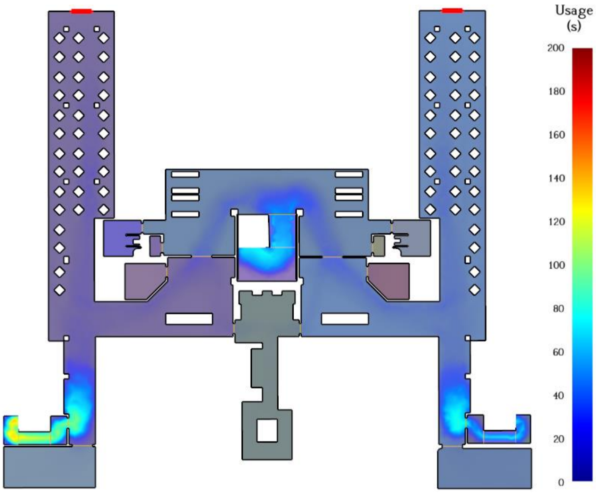

Figure B3. *Congested Areas on the Fifth Floor*

A visual representation of congestion levels on the fifth floor (roof terrace) of the Ordu Annex Courthouse is presented. Analyzing this visualization along with the roof terrace floor plan will help identify congested areas and understand how the layout of the dining hall and other areas on this floor contribute to congestion patterns.

EARLY VIEW

Appendix C: Simulation Visualizations (Flow Rates)

Appendix C presents visualizations generated from Pathfinder simulations, illustrating pedestrian flow patterns, congested areas, and flow rates at key points along the evacuation routes. These visualizations provide a deeper understanding of the spatial dynamics of the evacuation within the courthouse and support the identification and analysis of potential bottlenecks.

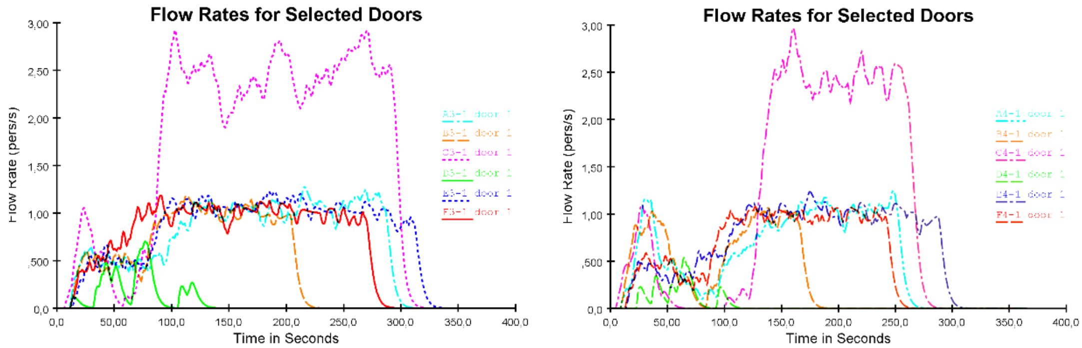

Figure C1. *Flow Rates of the Stairs between First and Second Floors (left) and the Stairs between Second and Third Floors (right)*

Figure C1 presents the measured flow rates (pedestrians per second) for each stairwell connecting the first and second floors (left) and the second and third floors (right). Analyzing these graphs helps in identifying bottlenecks and understanding the usage patterns of different stairwells during an evacuation. Peaks and plateaus in the flow rate curves can indicate areas of congestion or limited capacity.

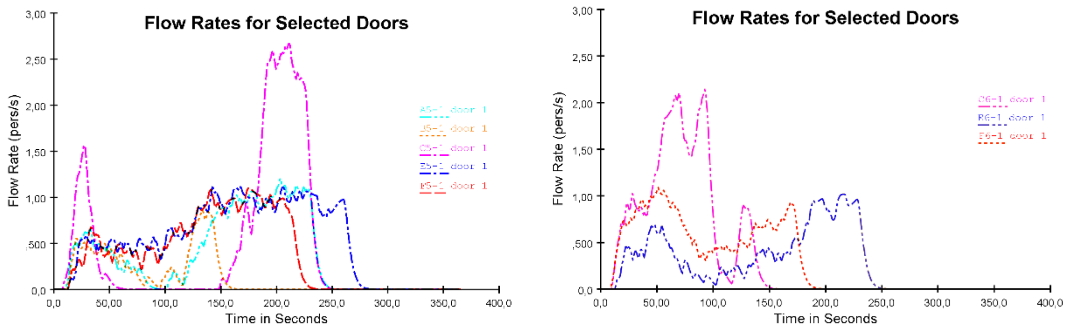

Figure C2. *Flow Rates of the Stairs between Third and Fourth Floors (left) and the Stairs between Fourth and Fifth Floors (right)*

Figure C2 shows the flow rates on the stairwells connecting the third and fourth floors (left) and the fourth and fifth floors (right). Comparing these flow rate patterns across different floor levels provides valuable insights into the vertical movement of occupants during an evacuation and highlights potential congestion points.