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CASE REPORT

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Evaluating the impact of gender segregation and egress design on mosque evacuation performance: an ABM study

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ABSTRACT

Mosques present unique evacuation safety challenges stemming from architectural features (e.g. open halls), fluctuating densities, and cultural practices like gender segregation. This study uses Agent-Based Modeling (ABM) to evaluate the impact of gender segregation on evacuation performance within the Ahmet Hamdi Akseki Mosque, Ankara (capacity: 5,000). The model integrates a realistic 3D environment, diverse agent demographics, and culturally specific spatial segregation. Four scenarios were compared: baseline segregation, inverted placement, mixed distribution, and baseline with additional Qibla exits. Simulations consistently identified critical congestion at Mahfil staircases and ground-floor exit merging points, resulting in significant evacuation delays for women in the baseline scenario due to the interplay of segregation and architectural constraints. The study quantifies performance differences across scenarios, assessing the effectiveness of occupant distribution strategies and added exits (including on the Qibla wall). Findings emphasize the need for performance-based design and targeted evacuation procedures. This ABM approach provides mosque designers and managers with a tool to evaluate interventions, optimize egress, and enhance safety in culturally sensitive contexts.

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Mosque evacuation; agent-based modeling; evacuation performance; mosque design; gender segregation; egress simulation; evacuation scenarios; bottleneck analysis

Introduction

Mosques serve as vital centers of worship and community in Islam, frequently hosting large congregations, which necessitates robust safety and emergency preparedness strategies. However, conventional building evacuation approaches often prove inadequate for mosques due to their unique characteristics (Alginahi et al., 2019; Nassar & Bayyoumi, 2012; Sagun et al., 2011). Architectural features like the 'Unity of Space" – expansive open prayer halls with multiple entrances – can lead to unpredictable crowd movement and bottlenecks (Toprakli & Satir, 2024; Topraklı et al., 2019). Furthermore, mosque occupancy fluctuates dynamically, challenging static evacuation models (Haron et al., 2012). Critically, diverse attendee demographics (age, gender, mobility) and culturally specific practices, notably **gender segregation** in prayer areas, demand tailored evacuation strategies (Chen et al., 2023; Toprakli & Satir, 2024) that integrate both social norms and architectural constraints. Past incidents further highlight these vulnerabilities (Alfakhry & Yahya, 2022; Sabah et al., 2018; Satır & Topraklı, 2021).

Despite growing research interest, significant gaps persist in understanding mosque evacuation dynamics, particularly concerning the interplay between cultural practices like gender segregation and architectural design within contemporary structures. While previous studies have examined

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mosque evacuation using various methods (e.g. (Alfakhry & Yahya, 2022; Alighadr & Fallahi, 2016; Nassar & Bayyoumi, 2012; Topraklı et al., 2019)), few have employed high-fidelity agent-based models to quantitatively assess the specific impact of gender-based spatial arrangements on egress performance considering detailed demographics and multi-floor layouts typical of modern mosques. Furthermore, research integrating BIM and ABM to analyze evacuation considering factors like gender segregation, as demonstrated by (Bina & Moghadas, 2021) in *Architectural Engineering and Design Management* for a conference hall setting, highlights the potential for simulation to explore these complex interactions, yet studies applying such detailed, culturally-informed ABM approaches specifically to mosques remain scarce.

This study addresses this gap by utilizing Agent-Based Modeling (ABM) to analyze evacuation dynamics within the Ahmet Hamdi Akseki Mosque in Ankara, Turkey (capacity: 5,000). We investigate how architectural features, occupant characteristics, and particularly spatial **gender segregation** influence evacuation processes. Specifically, this research aims to: (1) identify congestion bottlenecks influenced by segregation and egress configurations; (2) quantitatively assess how different spatial distributions (segregated vs. mixed) and architectural modifications (added exits) impact evacuation efficiency across demographics; and (3) investigate simulated occupant behavior's role in outcomes. This is achieved via a comparative analysis of four scenarios using a high-fidelity 3D model. The primary contribution is a detailed, culturally-informed ABM framework quantitatively evaluating gender segregation's impact on evacuation performance in a large, modern mosque, offering novel insights and a replicable methodology for safety assessment in similar culturally sensitive environments relevant to architectural engineering and design management. Ultimately, this study provides data-driven recommendations for mosque design and evacuation planning.

Literature review

Ensuring occupant safety within places of worship, particularly mosques, necessitates a comprehensive understanding of evacuation dynamics and the development of tailored safety strategies. Traditional evacuation models, often designed for conventional buildings, frequently fall short when applied to the unique context of mosques. This section reviews existing research on mosque evacuation, highlighting specific challenges and advancements in modeling techniques, drawing upon broader simulation literature and comparative studies in other large, complex spaces to position the current study.

Unique challenges in mosque evacuation

Mosques present a unique confluence of architectural, operational, and cultural factors that challenge conventional evacuation planning strategies and necessitate tailored approaches. A primary **architectural challenge** stems from the 'Unity of Space' concept, featuring expansive, open prayer halls often lacking compartmentalization (Toprakli & Satir, 2024; Topraklı et al., 2019). While symbolically significant, this openness can lead to unpredictable crowd flow, congestion, and disorientation, especially during high-occupancy events (Alginahi et al., 2019; Nassar & Bayyoumi, 2012). Effective planning must therefore carefully consider how the specific layout impacts flow, including vertical egress via stairs (Lujak et al., 2017; Roberts et al., 2021).

Compounding these architectural aspects are **fluctuating occupancy levels and specific cultural factors**. Unlike buildings with stable occupancy, mosque densities vary significantly due to daily prayer schedules and major religious events like Friday and Eid prayers, demanding dynamic rather than static modeling approaches (Haron et al., 2012; Toprakli & Satir, 2024). Furthermore, culturally specific demographics (varying age and gender distributions, e.g. (Onay, 2008)) and practices like gender segregation in prayer areas directly influence occupant distribution and egress paths, requiring explicit representation in realistic evacuation simulations (Chen et al., 2023).

architectural constraints and cultural factors (e.g. reluctance to place exits on the Qibla wall). This study's use of a detailed, multi-floor 3D model specifically analyzing interactions between distinct prayer areas (Harim/Mahfil) and circulation elements offers a more mosque-specific perspective than single-space studies. Acknowledging cultural practices like gender segregation was central to the scenario design, although limitations like excluding shoe retrieval remain (Section 6.1).

Further comparative research across diverse mosque architectures and cultural contexts is vital for developing robust, generalizable guidelines that respect local practices while maximizing safety.

Conclusions

This study employed Agent-Based Modeling (ABM) to analyze evacuation dynamics within the Ahmet Hamdi Akseki Mosque, specifically investigating the impact of spatial gender segregation. By simulating diverse scenarios within a realistic 3D model incorporating detailed agent characteristics and cultural norms, our research quantifies the evacuation challenges posed by this large, modern mosque's design and usage patterns. The findings confirm that architectural features like limited exits and stair capacity, particularly for the segregated upper Mahfil floor, combined with behavioral factors, lead to significant congestion and substantially longer evacuation times for occupants starting on the upper level (primarily women in the baseline scenario). The comparative analysis demonstrates that while adding ground-floor exits offers benefits, interventions must directly address the Mahfil egress path limitations to ensure equitable safety.

This research provides valuable, data-driven insights for architects, engineers, and emergency planners involved in mosque design and safety management. It underscores the inadequacy of relying solely on standard code compliance and highlights the necessity of using simulation tools like ABM to develop context-specific, culturally sensitive evacuation strategies. Key recommendations derived from this study include prioritizing increased and strategically aligned egress capacity for vertically separated floors, optimizing prayer hall layouts to facilitate smoother flow, and implementing procedural measures like targeted drills and clear wayfinding systems that account for observed congestion patterns and potential behavioral biases.

Limitations of the study

While providing significant insights, this study has inherent limitations. Firstly, the reliance on US-based demographic data (Bagby, 2020) and normative walking speeds (Bohannon & Williams Andrews, 2011) introduce uncertainty regarding direct applicability to the Turkish context and emergency conditions. Walking speeds during high-stress evacuations can deviate significantly from normative values, a factor not captured here. Secondly, the ABM software used (Pathfinder) has limitations in modeling complex psychological responses such as extreme panic, nuanced decision-making under stress (e.g. strong familiarity bias), or specific cultural behaviors like shoe retrieval, which could further influence evacuation times and congestion. Lastly, the exclusion of minors from the demographic data limits the model's representation of family groups or child-specific behaviors.

Future research directions

Addressing the limitations identified in this study points towards several key avenues for future research to enhance the realism and applicability of mosque evacuation modeling. **Firstly, acquiring localized empirical data** is crucial. This includes detailed demographic data for mosque attendees in specific regions like Turkey (incorporating minors), observed movement patterns (including walking speeds under simulated stress conditions), and quantification of culturally specific behaviors such as shoe retrieval times near exits. **Secondly, incorporating more sophisticated behavioral modeling** into ABM frameworks is needed. Future models should aim to simulate psychological

factors like panic effects on speed and decision-making (potentially leveraging frameworks like Islas-Toski et al., 2024), explicitly model cognitive biases such as familiarity preference in exit choice, and integrate family/group dynamics and assistance behaviors. **Thirdly, broader scenario testing** is essential for generalizability. This involves expanding simulations to encompass diverse mosque architectural typologies (historical/modern, varying sizes/layouts), different occupant densities corresponding to various prayer times/events, and a wider range of emergency triggers (including integrated fire/smoke or security threats). Testing the effectiveness of specific design interventions identified in this study (e.g. alternative Mahfil stair configurations) is also warranted. **Finally, rigorous validation** remains paramount; where ethically feasible, comparing simulation outputs against data from controlled drills or real-world incident analyses would significantly strengthen model credibility. Pursuing these directions, alongside incorporating detailed environmental factors and robust sensitivity/statistical analysis, will enable the development of more reliable, culturally attuned, evidence-based guidelines for safeguarding worshippers in mosques globally.

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Disclosure statement

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Appendices

Appendix A: Statistical analysis of evacuation times (Baseline Scenario S1)

This appendix presents the statistical tests conducted to analyze differences in individual agent evacuation times observed in the baseline simulation scenario (S1), which features typical gender segregation (women on Mahfil, men on Harim).

A.1 Comparison of evacuation times between genders (S1)

An **Independent Samples t-test** was performed to compare the mean evacuation times between male occupants (starting on the Harim floor) and female occupants (starting on the Mahfil floor). As variances between the groups were unequal (indicated by descriptive statistics and justifying the choice of Welch's t-test approximation), the test assuming unequal variances was utilized. The descriptive statistics and t-test results are summarized in Table A.1 and Table A.2, respectively.

Table A. 1. Descriptive statistics for evacuation time by gender (Scenario S1).

Group	Count	Sum	Mean (s)	Variance	Std. Deviation (s)
Men	3325	103137.18	69.85	1325.46	36.41
Women	1671	77142.18	195.51	2937.81	54.20
Total	4996	180279.35			

Note: Mean and Standard Deviation derived from t-test analysis inputs/outputs.

Table A. 2. Independent samples t-test results (unequal variances assumed) for evacuation time by gender (Scenario S1).

Comparison	Mean Difference (s)	t-statistic	Approx. df	p-value (2-tailed)	Significance ($\alpha = 0.05$)
Men vs. Women	−125.67	−85.57	2449	< 0.001	Statistically Significant (Reject H_0)

Interpretation: The results demonstrate a statistically significant difference in mean evacuation times between genders in Scenario S1 ($t(2449) = -85.57$, $p < 0.001$). Women starting on the Mahfil ($M = 195.51$s, $SD = 54.20$) took substantially longer to evacuate than men starting on the Harim ($M = 69.85$s, $SD = 36.41$), confirming the significant disadvantage associated with the upper-floor location and its egress path in this segregated layout.

A.2 Comparison of evacuation times between age groups within gender (S1)

Separate **One-Way ANOVAs** were conducted to determine if significant differences in mean evacuation times existed among the three age groups (18–34, 35–64, 65+) *within* each gender/location group.

Table A. 3. One-way anova summary for evacuation time by age group (men, Harim floor, S1).

Source of Variation	SS	df	MS	F	P-value	Significance ($\alpha = 0.05$)
Between Groups	1464.41	2	732.20	0.5523	0.5757	Not Significant
Within Groups	4404355.19	3322	1325.81			
Total	4405819.60	3324				

Table A. 4. One-way anova summary for evacuation time by age group (women, Mahfil floor, S1).

Source of Variation	SS	df	MS	F	P-value	Significance ($\alpha = 0.05$)
Between Groups	595.55	2	297.77	0.1013	0.9037	Not Significant
Within Groups	4905543.22	1668	2940.97			
Total	4906138.77	1670				

Interpretation: The ANOVA results indicate no statistically significant differences in mean evacuation times among the age groups for either men on the Harim floor ($p = 0.5757$) or women on the Mahfil floor ($p = 0.9037$) in Scenario S1. This lack of significant age effect within starting locations supports the interpretation that high-density congestion at bottlenecks was the primary factor limiting average evacuation speeds for all age groups in this baseline scenario.

Appendix B: stair and exit capacity assessment based on NFPA 101

An assessment of the mosque's egress capacity against **NFPA 101 (2018) Life Safety Code** requirements confirms potential limitations based on prescriptive calculations (Table B1). The total available exit width (1810cm) provides

only **72%** of the required width (2498 cm) for the total simulated occupant load of 4996 persons (using the capacity factor of 0.5 pers/mm or 5 mm/person from NFPA 101 Table 7.3.3.1 for level components). Similarly, the total available stair width (760 cm) provides only **59%** of the required width (1296.96 cm) for the 1671 Mahfil occupants (based on the baseline scenario S1 distribution and using the 0.3 pers/mm or 7.6 mm/person capacity factor for stairs). These calculated deficiencies underscore the potential for overcrowding and delays. This static assessment aligns with the dynamic congestion observed at stair and exit bottlenecks in the ABM simulations (see Section 4.1), further highlighting the importance of performance-based evaluation.

Table B. 1. Stair and exit capacity calculation based on (NFPA 101 – life safety code, 2024).

Exit	Width (cm)	Stair	Width (cm)
A	275.5	S1	190
B	275.5	S2	190
C	110	S3	190
D	244	S4	190
E	244		
F	110		
G	275.5		
H	275.5		
Sum	1810	Sum	760

Table B. 2. (NFPA 101 – life safety code, 2024) requirement (Table 7.3.3.1 capacity factors).

Egress Component	NFPA 101 Requirement (Table 7.3.3.1 Capacity Factors)	Occupant Load	Required Width (cm)	Provided Width (cm)	% Provided
Level Exits	5 mm/person	4996	4996 people * 0.5 cm/person = 2498	1810	72%
Stairs (Mahfil)	7.6 mm/person	1671 (Occupant Load of Mahfil in S1)	1671 people * 0.76 cm/person = 1296.96	760	59%

Appendix C: sensitivity analysis details

To assess the robustness of the main findings presented in Section 4 to plausible variations in key input parameters, a sensitivity analysis was conducted focusing on the baseline scenario (S1). This analysis systematically varied two primary parameters one at a time: Occupant Load (Density) and Walking Speed.

C.1 Parameters varied

- **Occupant Load:** The baseline load of 4996 agents was adjusted by ±10% (resulting in 4496 and 5496 agents, respectively) while maintaining the original demographic distributions and spatial assignments (S1 configuration). This tested sensitivity to variations in attendance density.
- **Walking Speed:** The baseline walking speeds for all agents (defined by age and gender in Table 2) were uniformly scaled by ±15% (i.e. multiplied by 0.85 and 1.15). This tested sensitivity to overall faster or slower population movement potential, acknowledging uncertainty relative to the normative speeds used.

C.2 Results

The impact of these parameter variations on the overall Total Evacuation Time (TET) for Scenario S1 is presented in Table C1 and visualized in Figure C1.

Table C. 1. Sensitivity analysis results: impact on total evacuation time (TET) for baseline scenario (S1).

Parameter Changed	Change Amount	Resulting TET (sec.)	% Change in TET from Baseline (310.3s)
Occupant Load	Baseline	310.3	–
	−10%	283.8	−8.54%
	+10%	345.8	+11.44%
Walking Speed	Baseline	310.3	–
	−15%	359.8	+15.95%
	+15%	271.8	−12.41%

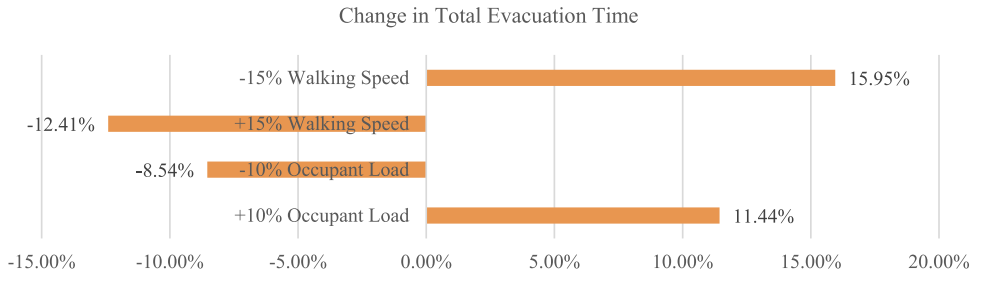


Figure C. 1. Percentage change in total evacuation time (TET) from baseline (310.3s) for sensitivity analysis variations. The chart visually represents the data from Table C1.

C.3 Interpretation

As Table C1 and Figure C1 show, the TET was sensitive to changes in both occupant load and walking speed, varying by approximately ±8–11% for a ± 10% load change and ±12–16% for a ± 15% speed change. However, qualitative analysis of the simulation outputs (heatmaps, flow patterns, relative group timings) for these sensitivity runs indicated that the fundamental conclusions drawn from the main study remained robust:

1. The primary **congestion hotspots** consistently occurred at the base of the Mahfil staircases and near the main Harim exits.
2. The substantial **relative difference** in evacuation times between occupants originating on the Mahfil versus the Harim persisted across all variations.
3. The **limited impact of age on mean evacuation times** (due to bottlenecking) within each starting floor was also consistently observed.

Therefore, this sensitivity analysis supports the conclusion that the core findings regarding bottleneck locations and the significant impact of the Mahfil egress path under segregation are robust to plausible (±10–15%) variations in occupant density and average walking speed.