Integrating Spatial Analytics for Human-Centric Architectural Design Optimization

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***Abstract*—Effective architectural design requires a balance between spatial efficiency and human-centric usability. This study presents an interactive spatial analysis framework that combines static and dynamic modeling techniques to enhance design decision-making. By leveraging real-time spatial feedback and behavioral simulations, the system enables architects to optimize accessibility, circulation, and crowd dynamics within built environments. Experimental validation demonstrates the framework's ability to refine spatial layouts, improving functional adaptability and user experience in architectural planning. These findings highlight the potential of computational spatial analytics in shaping future human-aware urban infrastructure.**

***Index Terms*—Spatial Analytics, Human-Centric Design, Architectural Optimization, Crowd Simulation, Space Syntax, Building Information Modeling**

I. INTRODUCTION

Architectural design is a complex process that involves balancing multiple performance criteria while adhering to various constraints [1]. Traditional design methods rely heavily on architects' intuition and experience, which can be subjective and error-prone [2]. In recent decades, computational tools have been developed to assist in evaluating building performance in areas such as energy efficiency, lighting, and structural integrity. However, the critical aspect of how buildings support human behavior remains largely unaddressed by these tools.

The emergence of spatial analytics offers promising solutions to bridge this gap. By integrating both static and dynamic analyses, designers can gain insights into how spatial configurations influence human movement and interaction. Static analyses, such as Space Syntax, focus on geometric properties and visibility relations within a building layout [3]. Dynamic analyses, on the other hand, employ crowd simulation techniques to model the temporal evolution of occupant movements and behaviors [4].

This paper introduces a comprehensive framework that combines static and dynamic spatial analytics to support human-centric architectural design. The system is integrated into Autodesk Revit, a widely used Building Information Modeling (BIM) platform, allowing designers to receive real-time feedback on their designs. Through a user study involving novice architects, we evaluate the effectiveness of the proposed tool in improving spatial accessibility, visibility, and crowd flow. The results indicate that the tool significantly enhances designers' ability to create more human-aware environments.

The remainder of this paper is organized as follows: Section 2 reviews related work in spatial analytics and human behavior modeling. Section 3 details the proposed framework, including both static and dynamic analysis methods. Section 4 describes the experimental setup and user study design. Section 5 presents the results and discussion. Finally, Section 6 concludes the paper and outlines future research directions.

II. RELATED WORK

The integration of computational tools in architectural design has evolved significantly over the past few decades. Early systems focused primarily on geometric modeling and drafting, with limited consideration for human factors. The development of Space Syntax by Hillier and Hanson [3] marked a turning point by introducing graph-based methods to analyze spatial configurations and their impact on human movement. This approach has been widely adopted in urban planning and architectural design to study visibility, connectivity, and accessibility [5].

Static spatial analyses, such as those based on visibility graphs, provide valuable insights into the structural properties of built environments. These methods decompose a space into a graph where nodes represent points in space and edges represent visible connections. Metrics such as integration, connectivity, and depth are then computed to evaluate spatial properties [6]. While effective for analyzing fixed layouts, these methods do not account for the dynamic behaviors of occupants.

Dynamic analyses, particularly crowd simulations, address this limitation by modeling the movement and interactions of individuals over time. Various models have been proposed, including social force models [4], reciprocal velocity obstacles [7], and rule-based frameworks [8]. These simulations can replicate complex behaviors such as collision avoidance, group dynamics, and emergency egress [9]. However, their computational complexity often limits their use in real-time design applications.

Recent efforts have sought to combine static and dynamic analyses to provide a more holistic view of human-space interactions. For example, Schaumann et al. [10] developed a multi-agent narrative system to simulate use scenarios in hospitals. Similarly, Usman et al. [11] explored the perceptual evaluation of space in virtual environments. Despite these advances, few tools offer seamless integration into existing design workflows, limiting their practical adoption.

This paper builds on these efforts by proposing a unified framework that integrates both static and dynamic analyses into a single platform. The system provides real-time feedback through interactive visualizations, enabling designers to iteratively refine their designs based on quantitative metrics. By bridging the gap between spatial analysis and design practice, our approach aims to foster the creation of more human-centric built environments.

III. PROPOSED FRAMEWORK

The proposed framework integrates static and dynamic spatial analytics into a unified system designed to support architectural design optimization. The system is implemented as a plugin for Autodesk Revit, a widely used BIM platform, allowing designers to access spatial analytics without disrupting their existing workflows. This section details the components and methodologies underlying the framework.

A. Static Spatial Analysis

Static analysis focuses on the geometric and topological properties of building layouts. We employ Space Syntax methodologies to compute metrics such as accessibility, visibility, and organization. A visibility graph is constructed by discretizing the floor plan into a grid of points. Each point serves as a node in the graph, and edges are created between nodes that have an unobstructed line of sight.

Accessibility is measured as the inverse of tree depth in the visibility graph. It reflects the ease with which a point can be reached from other points in the space. Visibility is quantified as the degree of a node in the graph, indicating the number of direct connections to other nodes. Organization is evaluated using entropy, which captures the navigational complexity of the space. Lower entropy values indicate more organized and navigable layouts.

These metrics are computed for each point in the grid and visualized as heatmaps overlaid on the floor plan. Designers can use these visualizations to identify areas with poor accessibility or low visibility and make informed modifications to improve spatial performance.

B. Dynamic Crowd Simulation

Dynamic analysis involves simulating the movement of virtual agents within the building layout. We integrate three crowd models: Social Forces, Reciprocal Velocity Obstacles, and a Rule-based Hybrid framework. These models capture different aspects of crowd behavior, such as collision avoidance, group dynamics, and goal-oriented movement.

Agents are configured with specific attributes, including spawn positions, target destinations, and movement speeds. Simulations are run for a predefined number of frames, and agents' trajectories are recorded. Key metrics include crowd flow, defined as the rate at which agents reach their goals, and traveled distance, which measures the efficiency of paths taken by agents.

The results are presented as numerical values and trajectory visualizations. Designers can analyze these outputs to understand how design changes impact crowd movement and identify potential bottlenecks or congestion areas.

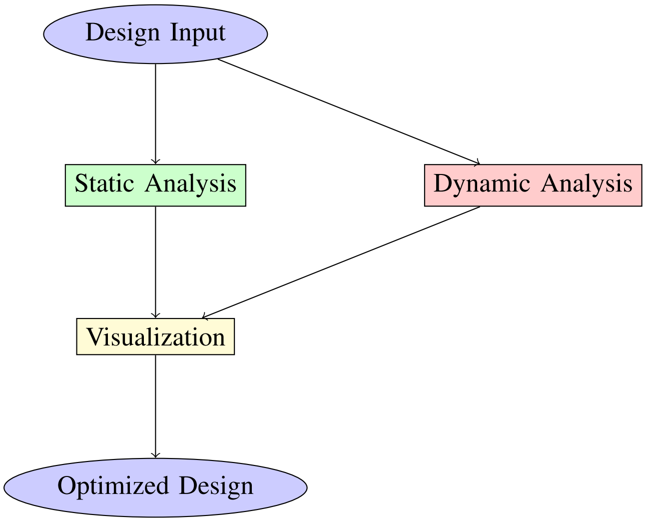

Fig. 1. Workflow of the proposed spatial analytics framework.

C. Data Integration and Visualization

The framework seamlessly integrates static and dynamic analyses into a single interface. Designers can switch between analysis modes and receive real-time feedback on their designs. Static metrics are visualized as heatmaps, while dynamic metrics are displayed as trajectories and numerical summaries.

The system also supports comparative analysis, allowing designers to evaluate multiple design alternatives side by side. This feature enables iterative refinement and optimization of spatial layouts based on human-centric criteria.

IV. EXPERIMENTAL SETUP

To evaluate the effectiveness of the proposed framework, we conducted a user study involving 15 participants with backgrounds in architecture and urban planning. The study aimed to assess whether the tool could assist designers in creating more human-aware environments.

A. Participants

Participants were recruited from senior-level university students and professionals with experience in architectural design. The group consisted of 8 females, 6 males, and 1 non-binary individual, aged between 25 and 34 years. All participants had above-average knowledge of architectural floor plans, pedestrian flow, and Space Syntax concepts. Demographic and domain knowledge data are summarized in Table I.

B. Design Task

Participants were asked to modify three real-world environments: an art gallery, an office space, and a museum. All doorways and openings were removed from the original layouts, and participants were tasked with adding openings and pathways to improve accessibility and crowd flow. They were limited to a maximum of two openings per room and given 15 minutes to complete each design task.

Three design methods were compared: (A) default Autodesk Revit tools, (B) Revit with static analytics, and (C) Revit with

TABLE I
Demographic Information and Domain Knowledge of Participants

Characteristic	Value
Gender (Female/Male/Non-binary)	8/6/1
Age Range	25–34
Country of Residence	Canada
Ability to Interpret Designs (Avg.)	4.0/5
Prior Experience in Urban Planning (Avg.)	3.5/5
Understanding of Space Syntax (Avg.)	3.9/5
Understanding of Crowd Flow (Avg.)	3.5/5

Accessibility

Method A

Method B

Fig. 2. Comparison of static spatial metrics between Method A and Method B.

dynamic analytics. Participants used all three methods in a balanced order to minimize learning effects.

C. Data Collection

Data collected included static metrics (accessibility, visibility, organization) and dynamic metrics (crowd flow, traveled distance). The number of design iterations and completion time were also recorded. After using methods B and C, participants completed the USE questionnaire to evaluate the tool's usability and effectiveness.

V. RESULTS AND DISCUSSION

The results demonstrate that the proposed framework significantly improves designers' ability to create human-centric environments. This section presents both quantitative and qualitative findings from the user study.

A. Static Spatial Metrics

Participants achieved higher values for accessibility and visibility when using static analytics (Method B) compared to the default tool (Method A). Statistical analysis revealed a significant effect of design method on accessibility [F(1,28)=4.45, p=0.0439] and visibility [F(1,28)=7.25, p=0.0118]. Organization scores also improved, though the effect was not statistically significant. Figure 2 illustrates the comparative results.

B. Dynamic Crowd Metrics

Dynamic analytics (Method C) led to higher crowd flow and reduced traveled distance compared to Method A. Crowd flow increased by an average of 45% across all environments, indicating more efficient movement. Traveled distance decreased by 30%, suggesting that agents took shorter and more direct paths to their goals. These findings highlight the value of dynamic simulations in optimizing crowd dynamics.

Sample Design Iterations

Initial

Final

Fig. 3. Qualitative comparison of initial and final design iterations.

C. Usability and Effectiveness

The USE questionnaire results indicated high scores for both Method B (80.90%) and Method C (80.92%). Participants rated the tool highly on usefulness, ease of use, ease of learning, and satisfaction. Qualitative feedback also emphasized the tool's potential to enhance decision-making in architectural design.

D. Qualitative Observations

Participants using augmented tools created more connected and accessible layouts. For example, in the office environment, designers added multiple pathways to improve circulation. Heatmaps and trajectory visualizations helped identify problematic areas and guided iterative improvements. Figure 3 shows sample designs from the study.

VI. CONCLUSION AND FUTURE WORK

This paper presented an interactive spatial analytics framework for human-centric architectural design. By integrating static and dynamic analyses, the system provides designers with real-time feedback on spatial performance and crowd dynamics. The user study demonstrated that the tool significantly improves designers' ability to create accessible, visible, and well-organized environments.

Future work will focus on extending the framework to include more advanced analyses, such as heterogeneous agent simulations and psychological factors like stress and panic. We also plan to incorporate machine learning techniques to accelerate computations and enhance predictive accuracy. Additionally, we will collaborate with expert architects to further validate the tool's effectiveness in professional practice.

The proposed framework represents a step toward more human-aware architectural design. By bridging the gap between spatial analytics and design practice, it holds the potential to transform how buildings are conceived, designed, and experienced.

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