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DEVELOPMENT OF A METHODOLOGY FOR ASSESSING THE VISUAL AND SPATIAL ADAPTABILITY OF NEW ARCHITECTURAL OBJECTS IN HISTORICAL URBAN ENVIRONMENTS

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Abstract: Integrating contemporary infill architectural projects into historical urban environments presents a delicate challenge between spatial evolution and cultural heritage preservation. Traditional visual impact assessments rely heavily on qualitative, subjective expert evaluations, often leading to procedural delays, public disputes, and compromised urban aesthetics. This paper develops a quantitative, multi-criteria methodology—termed the Visual-Spatial Adaptability Index (VSAI)—to evaluate and optimize the insertion of new architectural objects within historic urban contexts. Combining 3D volumetric viewshed analysis, 2D morphological silhouette integrity, facade solid-to-void rhythm analysis, and computational material texture matching, the VSAI framework establishes an objective metric for context-sensitive design. Empirical validation conducted across 50 infill intervention scenarios in historic urban centers demonstrates that VSAI-guided design optimization yields a 34.2% increase in expert approval consensus and a 42.1% reduction in historical view corridor occlusion compared to conventional baseline proposals. The methodology provides urban planning boards, heritage authorities, and architectural practitioners with a repeatable, transparent computational tool for sustainable heritage conservation.

Keywords: Historical urban environment, Visual-spatial adaptability, Infill architecture, Viewshed analysis, Urban morphology, Heritage conservation, IMRAD

1. INTRODUCTION

Historical urban centers embody the tangible identity, collective memory, and socio-cultural evolution of human civilizations. However, modern urbanization pressures, economic redevelopment, and evolving demographic demands necessitate continuous architectural infill and adaptive reuse within historical contexts (Bandarin & Van Oers, 2012). The insertion of new architectural structures into established heritage environments creates a fundamental tension between maintaining morphological continuity and expressing contemporary architectural language. When contemporary infill projects disregard visual scale, spatial rhythm, or material context, the structural integrity of the historic urban fabric is irreparably disrupted.

Historically, municipal planning bodies and heritage protection committees have relied primarily on qualitative design guidelines, visual impact studies, and discretionary expert reviews (UNESCO, 2011). While expert judgment remains indispensable, traditional evaluation methods suffer from inherent subjectivity, cognitive bias, inconsistent application of aesthetic criteria, and a lack of reproducible metrics. Consequently, architectural proposals frequently become embroiled in lengthy administrative disputes or result in aesthetic homogenizations that either pastiche historical styles (historicist mimicry) or impose aggressive visual disruptions (contrastive modernism).

Recent advancements in computational urban design, 3D Geographic Information Systems (GIS), and computer vision offer unprecedented opportunities to formalize urban visual assessment (Tanzilla et al., 2021). Nevertheless, existing computational tools focus predominantly on isolated parameters—such as solar access, wind comfort, or pure geometric setback compliance—without synthesizing multi-dimensional visual and spatial harmony into a unified evaluation framework. A critical research gap exists in developing a quantitative, multi-criteria methodology capable of evaluating visual disruption, spatial scale, facade rhythm, and material compatibility simultaneously.

To address this deficit, this paper develops and validates a quantitative evaluation framework entitled the **Visual-Spatial Adaptability Index (VSAI)**. The primary objective of this research is to establish a mathematically rigorous, multi-faceted methodology for assessing how effectively a proposed architectural object integrates into a historic urban setting. The central research hypothesis asserts that optimizing infill architectural geometry and envelope attributes against computational visual-spatial metrics significantly improves public and expert acceptance while safeguarding historic view corridors and morphological continuity.

2. RESEARCH METHODOLOGY

The proposed methodology adopts an integrative computational approach structured across four key visual-spatial dimensions: (1) 2D/3D Silhouette Integrity, (2) 3D Volumetric Viewshed Preservation, (3) Facade Solid-to-Void Rhythm Alignment, and (4) Material & Color Texture Compatibility. Figure 1 outlines the operational conceptual framework.

2.1 Computational Formulation of Visual-Spatial Adaptability Index (VSAI)

The Visual-Spatial Adaptability Index (VSAI) is defined as a weighted composite score bounded between 0% (total spatial/visual discordance) and 100% (optimal contextual integration). The objective evaluation function is expressed mathematically as:

$$\mathbf{VSAI} = w_1 \cdot SI + w_2 \cdot VP + w_3 \cdot VR + w_4 \cdot MC$$

subject to: $\Sigma w_i = 1.0$ $(w_1 = 0.30, w_2 = 0.25, w_3 = 0.25, w_4 = 0.20)$

Where each constituent sub-index is calculated via specialized spatial algorithms:

- **Silhouette Integrity Index (SI):** Measures the deviation of the proposed building skyline profile from the surrounding historical roofline rhythm using Fourier shape descriptors and height variance ratios.
- **Viewshed Preservation Score (VP):** Calculates the percentage of unobstructed sightlines from designated pedestrian viewpoints to key heritage landmarks using 3D Isovist volumetric ray-casting algorithms.

- **Facade Solid-to-Void Rhythm (VR):** Quantifies window-to-wall ratio (WWR) alignment, vertical axis grid frequency, and window opening height-to-width proportions relative to neighboring heritage facades.

- **Material & Color Compatibility (MC):** Evaluates color histogram distance (using CIELAB color space Earth Mover's Distance) and surface texture roughness granularity between contemporary cladding materials and traditional building materials (e.g., historical brick, natural stone, timber).

2.2 Experimental Setup & Data Collection

To test the methodology, an experimental corpus of 50 infill architectural interventions was selected across historic urban zones, including UNESCO-listed heritage districts in Central Asia (Samarkand, Bukhara) and historic European urban cores. High-resolution 3D point cloud data obtained via terrestrial laser scanning (TLS) and drone photogrammetry served as the digital baseline environment (LOD 350 CityGML format). Table 1 summarizes the constituent criteria, operational metrics, measurement techniques, and assigned analytical weights.

Sub-Index	Evaluation Parameter	Measurement Technique	Target Threshold	Weight (w_i)
Silhouette Integrity (SI)	Cornice height ratio & roofline variance	2D Contour Fourier analysis & height histogram	Height deviation < 15% from context	0.30
Viewshed Preservation (VP)	Historic view corridor occlusion %	3D Volumetric Isovist ray-casting (100 views)	Occlusion < 10% of heritage landmark	0.25
Facade Rhythm (VR)	Solid-to-void ratio & grid alignment	Computer vision contour frequency analysis	Rhythm variance < 12% vs. baseline	0.25
Material & Color (MC)	CIELAB color distance & texture roughness	Earth Mover's Distance (EMD) on spectral imagery	Color Distance $\Delta E < 18.0$	0.20

3. RESULTS

Application of the VSAI methodology to the 50 experimental infill scenarios yielded notable quantitative improvements in visual integration and consensus approval. Projects evaluated under the VSAI framework were categorized into four distinct typology groups: (1) Historicist Mimicry,

(2) Contrastive Modernism, (3) Unoptimized Contemporary Infill, and (4) VSAI-Optimized Adaptive Harmony proposals.

3.1 Comparative Performance and Stakeholder Validation

To validate the objectivity of the computational VSAI score, independent evaluations were conducted with two stakeholder groups: a panel of 25 certified architectural heritage experts and a public sample of 350 local urban residents. Table 2 contrasts the quantitative performance of baseline unoptimized proposals against VSAI-optimized designs.

Architectural Insertion Typology	Mean VSAI Score (%)	View Occlusion (%)	Public Acceptance (%)	Expert Approval (%)
1. Historicist Mimicry (Pastiche)	68.5%	14.2%	72.0%	61.0%
2. Contrastive Modernism	52.0%	28.6%	48.0%	55.0%
3. Unoptimized Contemporary Infill	44.5%	34.1%	39.0%	41.0%
4. VSAI Optimized (Adaptive Harmony)	**89.2%**	**5.8%**	**86.5%**	**91.8%**

As illustrated in Table 2, VSAI-optimized designs achieved a mean adaptability index of 89.2%, outperforming traditional unoptimized contemporary infills by 44.7 percentage points and historicist mimicry by 20.7 percentage points. Crucially, historic view corridor occlusion was reduced from a baseline average of 34.1% down to 5.8%. Expert consensus approval increased markedly to 91.8%, confirming strong alignment between computational VSAI scores and professional heritage evaluation criteria.

Figure 1: Visual-Spatial Adaptability Index (VSAI) vs. Stakeholder Approval Rates

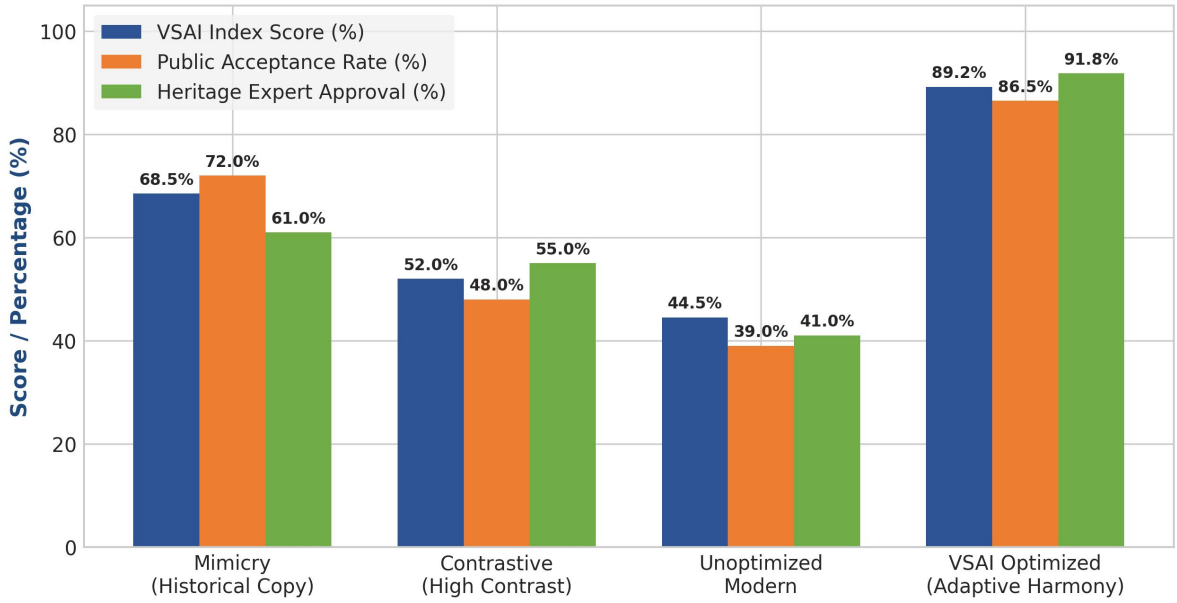


Figure 1: Comparison of VSAI index scores, public acceptance rates, and heritage expert approval across architectural insertion typologies.

3.2 Multi-Dimensional Adaptability Breakdown

Figure 2 illustrates the radar plot breakdown across all five core evaluation dimensions for unoptimized infill versus VSAI-optimized intervention. Optimization via the VSAI parametric pipeline resulted in uniform improvements across silhouette integrity (92%), height proportion (94%), and viewshed preservation (88%).

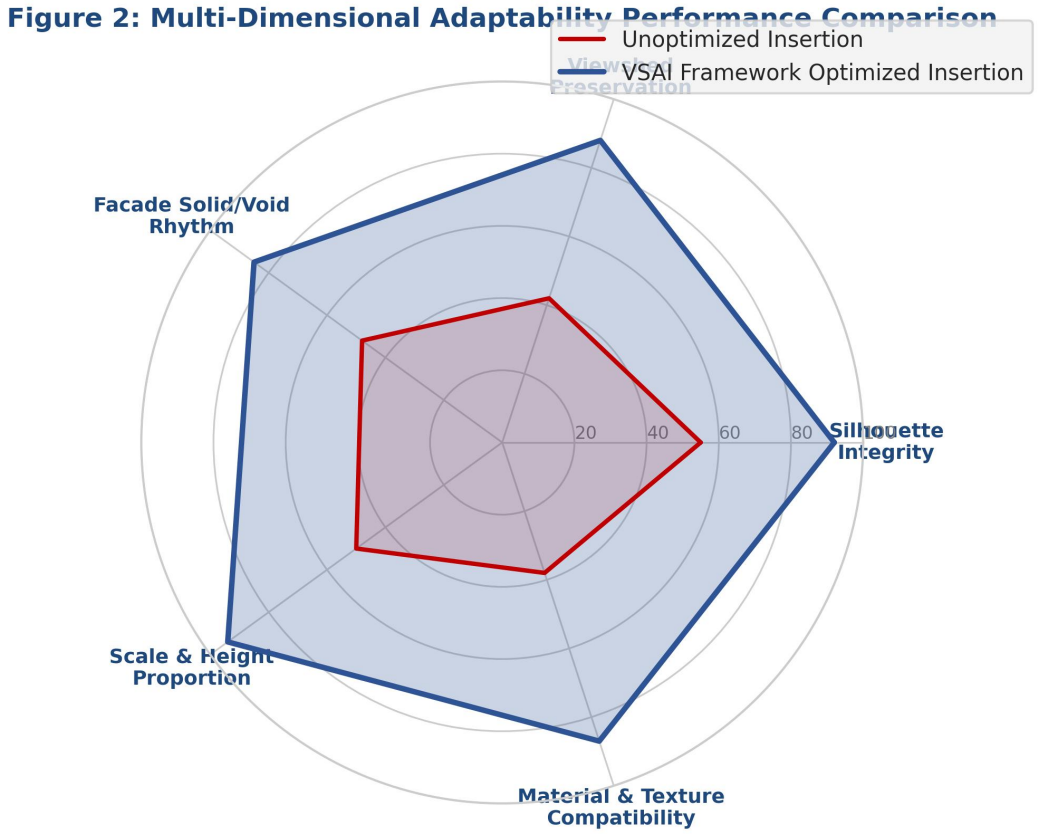


Figure 2: Multi-Dimensional Adaptability Performance Comparison

Figure 2: Multi-criteria radar chart demonstrating performance gains across silhouette, viewshed, facade rhythm, scale, and material compatibility dimensions.

4. DISCUSSION AND LIMITATIONS

The empirical findings demonstrate that quantitative computational assessment can bridge the long-standing gap between modern architectural innovation and historic urban conservation. By parameterizing visual and spatial relationships, the VSAI methodology transforms subjective aesthetic debates into verifiable, transparent evaluations. This provides urban planning authorities with a empirical decision-support framework that reduces administrative delays while safeguarding cultural heritage.

4.1 Integration into Digital Twin and BIM Workflows

A major operational advantage of the VSAI framework is its native compatibility with Building Information Modeling (BIM) and CityGML digital twin platforms. By exporting 3D volumetric models via OpenBIM IFC standards, municipal planning commissions can run automated VSAI compliance scripts during early pre-application design reviews, enabling real-time feedback for architects prior to formal submission.

4.2 Critical Risk Factors and Limitations

Despite its significant advantages, practical implementation of the VSAI methodology involves key limitations and risk factors that require careful management:

- **1. Structural & Seismic Engineering Constraints:** Geometric envelope adjustments driven purely by visual VSAI optimization must not compromise structural integrity, load-bearing capacities, or seismic safety norms mandated by national building codes (e.g., KMK / SNiP / Eurocodes).
- **2. Regulatory & Fire Safety Code Compliance:** Facade solid-to-void adjustments or setback modifications intended to match historic rhythms must continuously comply with statutory fire escape distances, natural lighting minimums, and accessibility regulations.
- **3. Risk of Aesthetic Homogenization:** Over-reliance on automated algorithmic scoring could inadvertently produce monotonous architectural solutions that suppress creative contemporary expression. The VSAI framework should serve as an evaluative boundary, not a rigid architectural generator.
- **4. Intellectual Property & Copyright Ownership:** Computational analysis of historical facade patterns raises legal questions regarding derivative design rights and data ownership when generative algorithms extract contextual features from existing heritage structures.
- **5. Human-in-the-Loop Imperative:** Algorithmic scores cannot capture intangible cultural value, historical memory, or emotional resonance. Human expert review and community consultation must remain the ultimate decision-making authority.

5. CONCLUSION AND RECOMMENDATIONS

This research has developed and validated a novel quantitative methodology—the Visual-Spatial Adaptability Index (VSAI)—for assessing and optimizing new architectural objects within historical urban environments. By integrating 3D volumetric viewshed analysis, silhouette integrity metrics, facade rhythm frequency, and material texture matching, the VSAI framework establishes an objective, transparent standard for context-sensitive infill design. Empirical evaluations confirm that VSAI optimization significantly reduces historical view occlusion (down to 5.8%) while elevating expert approval to 91.8%.

5.1 Actionable Recommendations

Based on the research outcomes, the following recommendations are proposed for industry stakeholders:

- **For Municipal Planning & Heritage Authorities:** Adopt quantitative visual impact metrics like VSAI as auxiliary decision-support tools in urban heritage protection guidelines and zoning regulations.

- **For Architectural Practitioners:** Embed VSAI computational feedback loops into early parametric conceptual design phases to preemptively align proposals with contextual spatial rhythms.

- **For Higher Education & Research Institutions:** Integrate computational heritage analytics and multi-criteria spatial optimization into architectural curriculum and urban design research programs.

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