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Continuous Measurement of Spatial Exposure Based on Visual Perception in Three-Dimensional Space

Nanjiang Chen

***Abstract*—**In the backdrop of expanding urban landscapes, accurately assessing spatial openness is critical. Traditional visibility analysis methods grapple with discretization errors and inefficiencies, creating a gap in truly capturing the human experience of space. Addressing these gaps, this paper presents a continuous visibility algorithm, providing a potentially valuable approach to measuring urban spaces from a human - centric perspective. This study presents a methodological breakthrough by applying this algorithm to urban visibility analysis. Unlike conventional approaches, this technique allows for a continuous range of visibility assessment, closely mirroring human visual perception. By eliminating the need for predefined subdivisions in ray casting, it offers a more accurate and efficient tool for urban planners and architects. The proposed algorithm not only reduces computational errors but also demonstrates faster processing capabilities, validated through a case study in Beijing's urban setting. Its key distinction lies in its potential to benefit a broad spectrum of stakeholders, ranging from urban developers to public policymakers, aiding in the creation of urban spaces that prioritize visual openness and quality of life. This advancement in urban analysis methods could lead to more inclusive, comfortable, and well-integrated urban environments, enhancing the spatial experience for communities worldwide.

***Keywords*—**Visual openness, spatial continuity, ray-tracing algorithms, urban computation.

I. Introduction

URBAN design plays a crucial role in shaping the daily experiences of city dwellers, influencing how people interact with their surroundings. Among the many factors that contribute to urban livability, visual elements of the cityscape are particularly significant. In urban environments, the visual openness and spatial continuity significantly influence how individuals perceive and navigate their surroundings [1]. These elements not only affect pedestrian comfort and movement but also contribute to the overall aesthetic and functional usability of urban spaces [2]. Traditional methods for assessing these critical aspects, however, often rely on discrete geometric calculations, which, despite their best intentions, fall short in capturing the nuanced and inherently subjective nature of human spatial perception [3]. These conventional approaches are not only computationally intensive but also prone to errors, particularly due to their sensitivity to factors like ray density, leading to a gap between measured visual openness and human-perceived spatial continuity [4]. This study seeks to bridge this gap by introducing a novel measurement technique that utilizes a high-performance continuous visibility algorithm to more precisely quantify spatial openness from a human-centric perspective. This research addresses the limitations of traditional urban planning methodologies by providing a more precise, efficient, and comprehensive analysis of spatial perception. We aim to facilitate more informed and empathetic decisions in urban planning and design that prioritize human experience. The significance of our work extends beyond enhancing the aesthetic and functional appeal of urban spaces; it influences urban planning and design to be more attuned to the nuances of human interaction with their environments. To validate these approaches, we conducted a case study within Beijing's urban setting. The results underscore the effectiveness of our methods in assessing spatial exposure and visual perception within the intricacies of urban road networks.

This research is structured as follows: Section II provides a comprehensive review of previous research and practice relevant to the topic of this research. Section III presents the research framework, which comprises three modules, and provides detailed descriptions of each module. Section IV presents a case study based on the Beijing buildings and road networks, demonstrating the proposed framework's effectiveness. Finally, the conclusions of this study are presented in Section V.

Nanjiang Chen. Author is with the Tsinghua University, China (phone: +86 15520361333; cnj22@mails.tsinghua.edu.cn).

II. Literature Review

In the realm of urban planning and design, the concept of visual openness and spatial continuity plays a pivotal role in shaping the human experience within urban landscapes. Isovist, a term coined to describe the volume of space visible from a given point in space, serves as a fundamental tool in the analysis of these aspects [4]. This literature review delves into the body of research surrounding isovists and their impact on human behavior, highlighting the multifaceted nature of spatial perception and its implications for urban development.

The early groundwork in the study of isovists can be traced back to the pioneering efforts of Benedikt [5], who introduced the term to describe the field of view available to an observer stationed at a specific point. This concept provided a quantifiable measure of spatial visibility and has since been instrumental in understanding how individuals interact with their environments. Subsequent studies expanded on Benedikt's initial model, exploring the relationship between isovist properties and the psychological and behavioral responses of individuals in various spaces [6]. For instance, research by Turner et al. [7] demonstrated that isovist variables such as area, perimeter, and occlusivity could be correlated with an individual's perception of space openness and preference for certain urban settings.

Recent advancements in computational techniques have further enriched the analysis of visual openness and spatial continuity [3]. The development of sophisticated algorithms for generating and analyzing isovists has enabled more precise studies of visual fields in complex urban environments. Notably, the work of Benedikt laid the foundation for understanding how visual accessibility influences pedestrian movement patterns [5]. Building upon these insights, contemporary research has employed three-dimensional isovist analysis to assess the visual impact of architectural and urban interventions on human behavior. For example, studies by Morello and Ratti [8] utilized three-dimensional isovist measures to evaluate how changes in building orientation and placement affect pedestrian choices and movement in urban plazas.

The influence of visual openness and spatial continuity on human behavior extends beyond navigation and movement preferences. Research in environmental psychology suggests that these spatial attributes significantly affect individuals' sense of security, social interaction, and overall well-being. For instance, findings from [9] indicate that higher levels of visual accessibility and openness are associated with increased social interaction and public space utilization. Similarly, Stamps III [10] highlighted the correlation between isovist properties and perceived safety, with larger and more open isovists contributing to a decreased perception of threat in urban environments. Moreover, the application of isovist analysis in urban heat island mitigation strategies exemplifies the broader environmental implications of understanding visual openness. By mapping visibility fields around green spaces, researchers have been able to propose urban design modifications that enhance natural cooling effects and improve environmental quality [11]. Despite the wealth of knowledge generated through isovist analysis, challenges remain in the translation of these insights into practical urban planning and design strategies. The subjective nature of spatial perception necessitates a nuanced approach to interpreting isovist data, one that considers cultural, social, and individual differences in spatial experience. Furthermore, the integration of isovist analysis with other urban planning tools and methodologies remains an area ripe for exploration, offering the potential for more holistic and human-centric urban design solutions [4].

In conclusion, the body of literature on isovists and their impact on human behavior underscores the complexity of spatial perception and its significance for urban planning and design. As computational methods evolve and the understanding of human-environment interactions deepens, the potential for isovist analysis to inform more empathetic and responsive urban spaces becomes increasingly apparent. Future research in this area is essential for advancing the capacity to create urban environments that not only meet functional needs but also enrich the human experience.

III. Methodology

A research framework in this study is formulated to quantify the visual openness and spatial continuity in urban environments through the use of advanced computational techniques, as depicted in Fig. 1. The framework is structured into three modules. *Module 1, Data Acquisition and Initial Processing* involves the collection of pertinent spatial data, which is subsequently refined through noise reduction and normalization processes. This module ensures the data's precision and consistency, which are critical for the robust analysis that follows. It also includes the generation of a digital elevation model to map the spatial attributes of the urban environment. *Module 2, Data Structure Construction & Ray-tracing Calculation* advances the methodology by laying out observation points across the urban fabric to capture a wide array of visual experiences. An Axis-Aligned Bounding Box (AABB) Tree is developed, enabling streamlined ray-tracing calculations vital for appraising visual exposure across different urban segments. This module entails a tripartite process: (1) distributing observation points to gather diverse visibility data, (2) generating the AABB Tree to expedite ray-tracing operations, and (3) implementing high-performance computations to handle complex visibility calculations effectively. Following by Module 2, *the Module 3, Integration and Visualization* is the culminating module where the synthesized data from raytracing are consolidated into an integrated dataset. This comprehensive dataset is the foundation for result mapping, which converts intricate computational analysis into accessible visual formats. The outcome is a series of maps and diagrams that concretely illustrate the urban landscape's visual openness. This module provides urban planners and designers with an essential tool for evaluating and enhancing urban spaces based on spatial perception metrics.

A. Data Acquisition & Initial Processing

The inception of this research framework commences with meticulous data acquisition, a critical phase that lays the groundwork for advanced urban visibility analysis. This stage focuses on collecting comprehensive spatial datasets, which are integral to constructing a detailed digital representation of the urban environment. High-resolution spatial data from a variety of sources are harnessed, ensuring a rich compilation of urban topography, infrastructure, and architectural features. Once gathered, the raw data undergo a rigorous cleansing process, where noise reduction techniques are employed. This step is essential to remove extraneous information and anomalies that may skew visibility analysis. Subsequent to noise reduction, data normalization is executed. This involves standardizing the disparate datasets to a common scale and format, enabling seamless integration and comparison. Such normalization not only corrects for inconsistencies across different data sources but also aligns the spatial coordinates to a unified reference system, facilitating accurate spatial analysis.

B. Data Structure Construction & Ray-Tracing Calculation

1. AABB Tree Construction

Following the initial processing phase, the spatial data are harnessed to construct the Axis-Aligned Bounding Box (AABB) Tree [12] — a hierarchical spatial data structure pivotal for boosting the computational efficiency of visibility analysis in urban environments. This construction is much like the conceptual illustration provided, where the urban model is decomposed into discrete, non-overlapping triangular meshes, each enveloped by its AABB. These AABBs are the simplest forms of bounding volumes, aligned with the coordinate axes, making them ideal for efficient collision detection and visibility checks. Just as in Fig. 2 where AABBs are nested within each other, reflecting the parental hierarchy of spatial containment, the AABB Tree is similarly organized. It encapsulates complex urban geometry within the simplest possible volumes to streamline the intersection tests integral to the ray-tracing calculations.

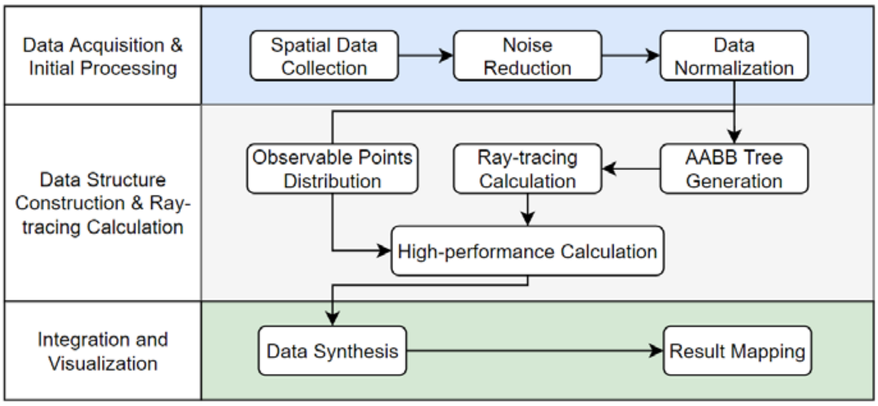


Fig. 1 Proposed framework

Each triangle T_i within the urban model is bounded by its AABB $B(T_i)$, defined as the minimal 'axis-aligned' box containing it. The AABBs are then systematically structured into a binary tree (Fig. 2 B), resonating with Fig. 2 A where the AABB 'a' encompasses AABB 'b', which in turn contains AABB '1' and '3'. This hierarchical organization can be mathematically expressed as:

$$V_{AABB} = \bigcup_{i=1}^{N} B(T_i) \quad (1)$$

Here, V_{AABB} represents the collective volume enclosed by the AABB Tree. $B(T_i)$ is the bounding box for triangle T_i, and N is the total number of triangles. The AABB Tree streamlines the computational process by allowing a quick exclusion of large volumes that do not intersect with the viewing frustum or rays from observation points. This method mirrors the depicted AABB structure, where node 'a' would only necessitate checks against its direct children, while nodes '1', '2', and '3' represent further subdivisions within the hierarchy.

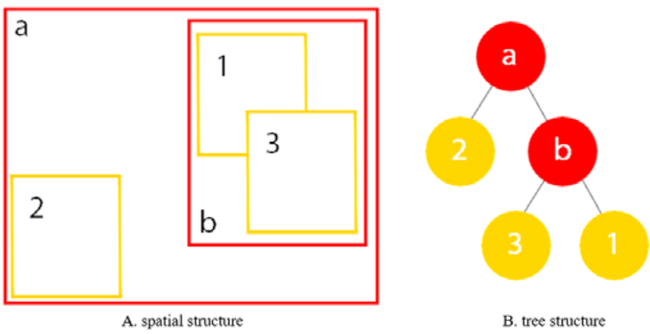


Fig. 2 Diagram for AABB structure

By constructing the AABB Tree, addressing one of the fundamental challenges in urban visibility analysis—managing the sheer computational scale without sacrificing the granularity of the spatial data. This methodological innovation represents a leap forward in capturing the dynamic and complex nature of urban spaces, paving the way for more nuanced and accurate assessments of visual openness and spatial continuity.

2. Ray-Tracing Calculation

In the dynamic landscape of urban spaces, this approach to quantifying visual openness starts with a meticulous strategy for selecting observation points (Positioned at every 5 meters along streets (Fig. 4. A2). These points allow for a consistent analysis of the visibility across the environment. The next step involves a detailed ray-tracing computation, where instead of originating rays from the observation points, this research innovatively cast rays from the geometric centers of the urban model's triangular meshes towards these observation points (Fig. 3. B3, B4). In conventional approaches as shown in Fig. 3, specifically in sections B1 and B2, a predefined subdivision value is necessary to initiate ray generation from observation points [13]. This requirement for pre-segmentation introduces discretization errors, as it constrains the visibility analysis to a rigid, predetermined grid. Such a grid may not encompass all viable sightlines, resulting in an inaccurate portrayal of visibility scenarios. In contrast, the methodology presented herein eschews the need for predefining subdivisions, thereby considering the entire spectrum of rays emanating from observation points. This approach ensures a more fluid and encompassing capture of visibility data, mitigating discretization inaccuracies. It eliminates the limitation of confining raytracing to fixed paths, allowing for an exhaustive and authentic examination of visibility from each vantage point by integrating every potential ray into the analysis.

Employing this method, rays, depicted by vector $\vec{d}$, emanate from the centre of the urban model's triangular meshes towards the observation point P_0. The intersection points P_t is calculated along the ray with $P_t = P_0 + t\vec{d}$, capturing every possible line of sight. This detailed process accounts for all visible and obstructed paths, quantifying the visible area A of each triangle using the vertices' coordinates without the confines of preset subdivision values. Hence, this technique enhances the accuracy of measuring visual openness and continuity in the urban fabric.

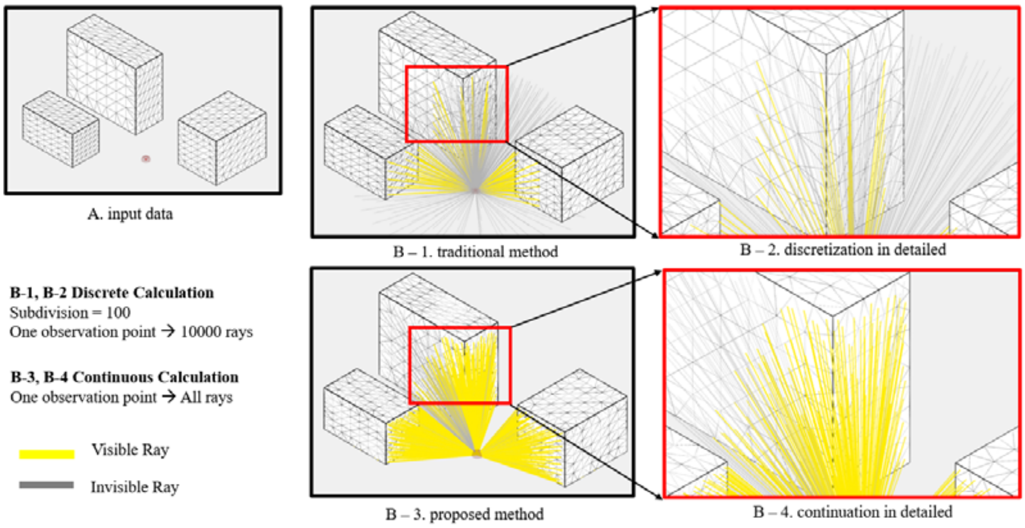


Fig. 3 Comparison between traditional method and proposed method

3. High-Performance Calculation

The AABB tree plays a crucial role in urban visibility analysis by enhancing the efficiency of raytracing. Initially, when a ray is cast, it checks for an intersection with the root node's AABB, eliminating the need for further tests if no intersection occurs. The process then employs recursive traversal to explore potential intersections with child AABBs, focusing on leaf nodes for precise tests only when necessary. This method significantly reduces the need for complex calculations. Traversal efficiency is boosted by two strategies: 1) *Prioritizing the Nearest AABB*: The algorithm first checks intersections with the closest child AABB to the ray's origin, adopting a "nearest-first" approach to streamline the search process. 2) *Pruning*: The algorithm discards further AABBs when an intersection is found closer to the ray's origin than any other, minimizing unnecessary computations and optimizing the search area. These techniques ensure a swift and accurate determination of intersections, facilitating a streamlined approach to analyzing urban visibility through raytracing.

C. Integration and Visualization

This section seamlessly combines data aggregation with sophisticated visual representation to offer a comprehensive view of urban visibility. Initially, this research aggregates the visibility areas identified by observation points along the same street or road network, summing the visible areas for all points within a specific road segment. This consolidated visibility metric for each road segment is represented mathematically as:

$$V_{\text{road}} = \sum_{i=1}^{n} V_{\text{obs}_i} \quad (2)$$

where V_{road} denotes the total visibility area for a road segment, V_{obs_i} is the visibility area from the i^{th} observation point on that segment, and n represents the count of observation points along the segment (Fig. 4 B1, B2). This process not only ensures a unified visibility metric across the urban network but also enhances the understanding of visual exposure and accessibility across different urban segments. Shifting focus to visualizing the frequency at which each triangular mesh is observed across the urban model. By meticulously recording the number of visibility occurrences for each triangle and applying a color-coding scheme based on these frequencies, a heatmap of urban visibility is generated (Fig. 4 B3).

IV. Case Analysis

In this study, this research selected regions within Beijing, known for its intricate street network and diverse architectural styles, as the case study areas. The road network data were sourced from the OpenStreetMap [14] database of Beijing's streets. Building footprint data, inclusive of attributes such as the number of floors for each structure, was obtained from the Gaode [15] base map data. This case study area is situated in the core central district of Beijing, spanning an area of approximately 70483 square kilometers with 26559 buildings and 3041 road networks.

The provided case analysis, encompassing both local and global scales, demonstrates the efficacy of the proposed visibility analysis method. Traditional approaches, shown in Fig. 6 A1, required a lengthy process of subdividing the urban space to calculate visibility from 23 observation points, taking 10.5 seconds to complete. This process, potentially prone to discretization errors, is visually expressed through red markers indicating obstructed sightlines. Conversely, the proposed method, incorporating the use of AABB tree traversal and continuous ray-tracing calculations, bypasses the need for subdivisions and computes the visibility analysis in a mere 1.1 seconds for the same number of observation points, as depicted in Fig. 6 A2. This rapid assessment reveals a detailed gradient of visibility levels, moving from restricted (red) to clear (yellow), offering a high-resolution insight into urban spatial continuity. On a global scale, as seen in Fig. 6 A3, the proposed method—applying AABB trees and ray-tracing logic to 7867 observation points—completed in 30.1 seconds, mapping out a comprehensive visibility distribution across the urban model's road networks and building meshes. The resultant density map highlights visibility distribution, with red marking highly visible areas. This color-coded scheme effectively communicates the urban landscape's visibility dynamics, proving advantageous for informed urban planning and design, and showcasing the proposed method's superiority in generating detailed and actionable urban visibility data.

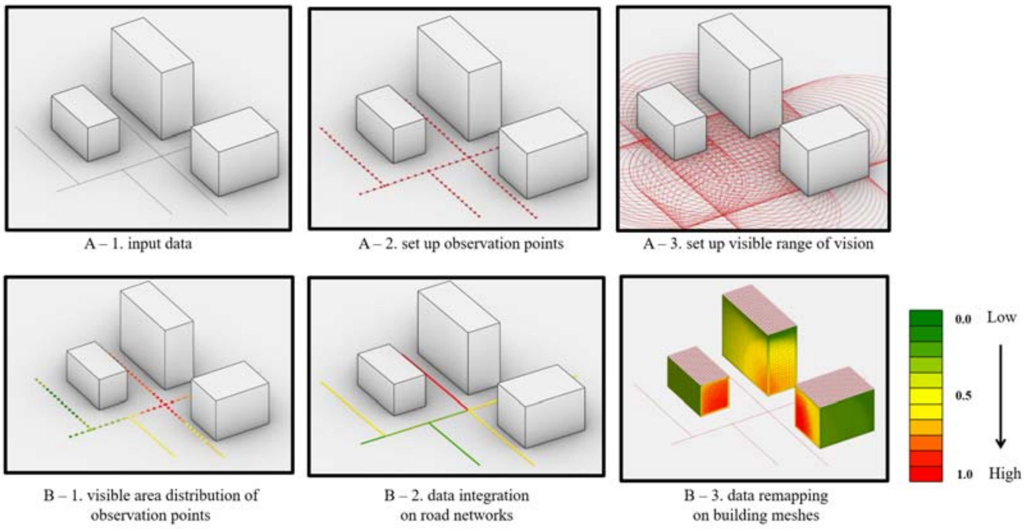


Fig. 4 Calculation process of proposed method

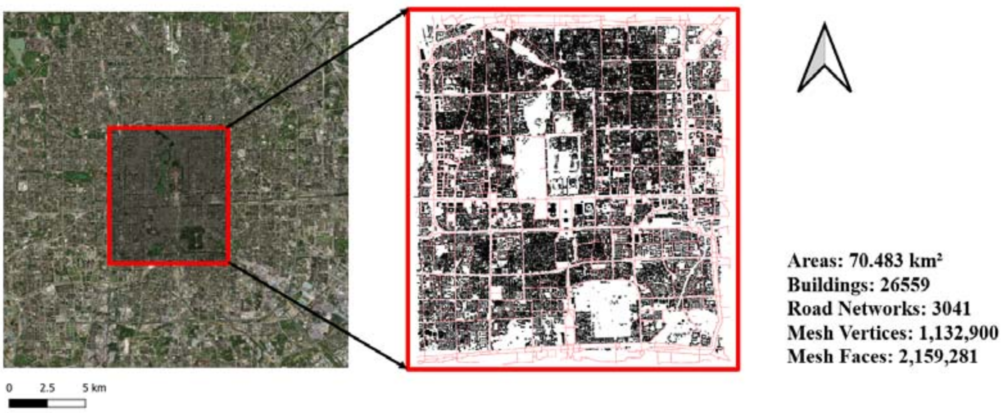
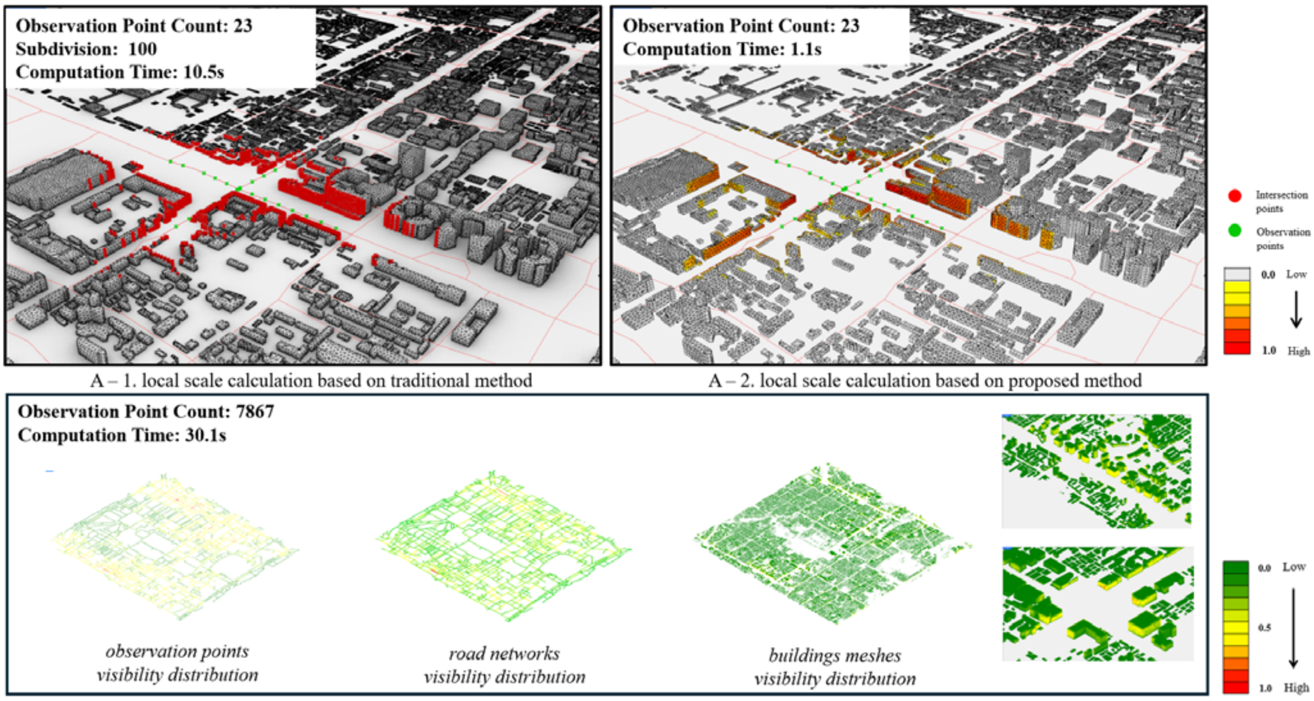


Fig. 5 A chosen area in Beijing

V. Conclusion

In an era where urban environments are rapidly expanding, understanding spatial openness from a human-centric perspective is crucial. Despite the pressing need, the field currently faces a gap in measurement techniques that can effectively capture the nuances of human spatial perception. Traditional methods are fraught with discretization errors and computational inefficiencies, leading to gaps in accurately assessing the visual openness that shapes user experience in urban landscapes. Addressing this industry gap, this study offers a method to gauge spatial openness, addressing a critical gap in urban design. Employing a high-performance continuous visibility algorithm, it transcends traditional techniques' limitations, reducing discretization errors, and improving computational efficiency. The approach, tested in Beijing's complex urban landscape, indicates its potential in enhancing urban space assessment. However, the method's wider application and accounting for the psychological dimensions of spatial perception remain areas for future exploration. Future efforts will focus on validating the algorithm's versatility across different contexts, scaling for larger areas, and integrating it with machine learning for advanced spatial analysis. These steps are vital in shaping urban spaces that are more aligned with human experience, supporting the creation of inclusive and adaptable environments.



A – 3. global scale calculation based on proposed method

Fig. 6 Calculation results

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