A Digital Twin-Driven Optimization of Urban Blue-Green Networks for Healthy Cities: A Multi-Scale Accessibility and Visibility Analysis Framework

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***Abstract*—As cities around the world continue to expand, creating healthier urban environments has become a central challenge for sustainable development. Blue-green networks—systems of interconnected parks, rivers, wetlands, and green corridors—serve as essential ecological infrastructure in cities and play a critical role in improving both the physical and mental well-being of residents. Despite their importance, current planning and design approaches for these networks often lack detailed and systematic methods for evaluation and optimization, which limits their ability to fully deliver health benefits. The rise of digital twin technology offers a powerful new way to tackle this complex challenge. This study proposes a multi-scale optimization framework for healthy urban blue-green networks driven by digital twins. The framework integrates several advanced analytical tools: the spatial data processing power of Geographic Information Systems (GIS), the urban morphology analysis capabilities of Space Syntax, and computer vision techniques that capture how people perceive the built environment. Using a representative city as a case study, the research constructs a high-fidelity urban digital twin model by combining multiple sources of heterogeneous data, including remote sensing imagery, built environment information, and population distribution datasets. Based on this digital model, the study performs systematic simulations and optimization analyses of blue-green network accessibility and visibility across three spatial scales: regional, district, and local. The findings demonstrate that the proposed framework can effectively detect weak connections and service gaps within existing blue-green network layouts. It can also precisely evaluate how different spatial intervention strategies—such as adding new entrances to green spaces, improving pedestrian pathways, or regulating building heights—may influence the health benefits experienced by residents. By simulating these interventions, the system can generate spatial optimization strategies that balance both equity and efficiency in urban service provision. Overall, this research provides planners and decision-makers with a quantifiable, interactive, and iterative tool for designing healthier cities. At the same time, it presents a practical example of how digital twin technology can be deeply applied in the field of urban ecological environments, supporting a shift toward more scientific, data-driven, and refined approaches to urban planning and design.**

Keywords—Digital Twin; Healthy City; Blue-Green Network; Spatial Accessibility; Spatial Visibility; Multi-Scale Analysis

I. INTRODUCTION

Against the dual pressures of rapid global urbanization and increasing public health concerns, the concept of Healthy Cities has gradually shifted from an aspirational vision to a central objective in contemporary urban governance [1]. The Healthy Cities initiative promoted by the World Health Organization (WHO) emphasizes that a city should function as a living system — one that continuously improves its physical and social environments while expanding community resources so that residents can support one another and reach their full potential [2]. Within this framework, Urban Green and Blue Infrastructure (GBI)—the ecological network formed by parks, forests, rivers, lakes, and other natural elements—has gained growing attention as a key Nature-based Solution (NbS) for urban sustainability [3]. A substantial body of research demonstrates that well-designed blue-green spaces can mitigate urban heat island effects, improve air quality, and reduce environmental noise. At the same time, they provide spaces for recreation, social interaction, and physical activity, thereby contributing significantly to both the physical and psychological well-being of urban residents [4,5].

Despite broad consensus regarding the health benefits of blue-green networks, their planning and implementation continue to face several persistent challenges. One major issue is the uneven spatial distribution of blue-green resources, which often leads to environmental justice concerns. While some communities benefit from convenient access to nearby green and blue spaces—sometimes referred to as "proximity-induced amenity" — others experience limited access due to long travel distances or inadequate transportation connections, resulting in "proximity-induced disamenity" [6]. Another problem lies in the fragmented connectivity of many blue-green systems. Parks, waterways, and green corridors are frequently separated from residential neighborhoods by major roadways or dense building clusters, which reduces actual accessibility compared with what planners initially intended. In addition, the visual accessibility, or visibility, of blue-green spaces is often constrained by the surrounding built environment. When buildings block views toward natural spaces, their potential benefits—such as reducing psychological stress or providing visual relief within dense urban landscapes — may be significantly weakened [7].

These challenges stem in part from the limitations of traditional planning approaches. Conventional evaluation indicators, such as the green space ratio or per capita park area, tend to provide static and macro-level assessments.

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While useful for broad planning guidance, they often fail to capture the fine-grained, real-world experiences of residents moving through urban space. As a result, planners lack tools that can dynamically simulate residents' spatial interactions with blue-green environments or quantitatively predict the health outcomes associated with different planning scenarios.

Recent advances in Digital Twin technology present a promising pathway for addressing these limitations. By creating a high-fidelity virtual representation of the physical city, a digital twin enables the integration of multi-source heterogeneous data, the simulation of complex urban dynamics, and the testing of alternative planning interventions before they are implemented in reality [8,9]. In the field of urban planning and management, digital twins have already demonstrated significant value in areas such as traffic management, emergency response, and infrastructure maintenance [10]. At the same time, methods for assessing the health-related performance of blue-green spaces have continued to evolve. These include GIS-based network accessibility analysis, 3D isovist analysis derived from spatial modeling, and computer vision or machine learning approaches for semantic analysis of urban imagery [7].

Although considerable progress has been made, clear theoretical and practical gaps remain. Many existing studies focus on a single spatial scale or a single analytical dimension. For instance, regional-scale accessibility analyses may identify broad patterns of green space distribution but provide limited guidance for design interventions at the neighborhood or street scale. Similarly, research that concentrates solely on accessibility often overlooks the important psychological and perceptual impacts associated with visibility of natural elements in the urban landscape. More importantly, there is still a lack of an integrated analytical framework that uses digital twin technology as a foundation to systematically combine multi-scale and multi-dimensional evaluations of blue-green networks and translate those insights directly into health-oriented planning decisions. This gap constrains the ability of cities to fully realize the potential health benefits of blue-green infrastructure and slows the transition toward more data-driven, refined, and people-centered urban planning practices.

To address these challenges, this study aims to develop and validate a digital twin-driven multi-scale optimization framework for urban blue-green networks, with the ultimate goal of maximizing health benefits for urban residents. The framework places residents' exposure to blue-green environments at the center of evaluation and focuses on two key spatial dimensions: spatial accessibility and spatial visibility. Within a unified digital twin platform, the study explores how different analytical models can be integrated and applied collaboratively across three spatial scales — regional, district, and local. This approach seeks to enable comprehensive diagnosis of blue-green network performance, rigorous evaluation of planning strategies, and the generation of scientifically grounded optimization solutions.

Specifically, the research addresses three core questions:

- How can an urban digital twin model be constructed to effectively support multi-scale analysis of blue-green networks?
- How can multiple analytical algorithms be integrated within this model to systematically evaluate the accessibility and visibility of blue-green infrastructure?
- How can insights derived from multi-scale analysis inform practical decision-making for health-oriented optimization of urban blue-green networks?

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature on healthy cities, digital twin technologies, and methods for evaluating blue-green spaces. Section 3 introduces the digital twin-driven multi-scale analytical framework and the core methodologies developed in this study. Section 4 presents a case study of a representative city to demonstrate the application process and analytical results of the framework. Section 5 discusses the findings in depth, highlighting their implications for urban planning and design as well as their methodological contributions. Finally, Section 6 summarizes the main conclusions of the study and outlines potential directions for future research.

II. Literature Review

A. *Healthy Cities and the Health Benefit Pathways of Blue-Green Infrastructure*

The promotion of the Healthy City concept has gradually shifted the focus of urban planning from traditional physical space construction toward a broader concern for human well-being and overall quality of life. Within this context, Urban Blue-Green Infrastructure (GBI) — a core component of urban ecosystems — has received increasing attention for its diverse health benefits. Studies across multiple disciplines have consistently demonstrated a positive relationship between residents' exposure to blue-green environments and improvements in public health. These benefits are commonly explained through four major pathways.

The first pathway is reducing harm. Blue-green spaces can regulate the urban microclimate and alleviate the urban heat island effect through processes such as vegetation transpiration and water evaporation [11]. At the same time, vegetation helps capture airborne particulate matter and absorb harmful gases, which contributes to better air quality and lower environmental noise levels. Together, these functions create a safer and more comfortable living environment for urban residents [12].

The second pathway is restoration, which is mainly supported by two influential theories in environmental psychology. Attention Restoration Theory (ART) proposes that natural environments help individuals recover from mental fatigue caused by prolonged directed attention. Natural settings provide qualities such as a feeling of "being away," effortless fascination, spatial extent, and compatibility with personal needs, all of which help restore cognitive capacity [13]. Stress Reduction Theory (SRT) further suggests that contact with nature — especially environments that include water elements — can trigger positive emotional responses, reduce stress, and support the recovery of physiological systems [14].

The third pathway is building capacities. Public blue-green spaces such as parks and waterfront areas provide important venues for social interaction. These environments encourage communication among community members, strengthen neighborhood relationships, and increase social capital. Such social connections are widely recognized as important factors in improving mental health and reducing feelings of loneliness and isolation [15].

The fourth pathway is encouraging physical activity. Blue-green environments offer attractive and accessible settings for activities such as walking, jogging, cycling, swimming, and boating. These opportunities for regular exercise contribute to reducing the risk of chronic diseases, including obesity and cardiovascular conditions [16].

Together, these four pathways interact and reinforce one another, forming the theoretical basis for understanding how blue-green infrastructure can improve the overall health of urban populations. They also provide the conceptual foundation for the optimization objectives pursued in this study.

B. Urban Digital Twin: From Concept to Application

The concept of the digital twin originated in the field of industrial manufacturing, where it was used to create highly detailed virtual replicas of physical objects in order to monitor, simulate, and optimize their performance throughout the product lifecycle [8]. With the rapid advancement of Information and Communication Technologies (ICT), this concept has been extended into the urban domain, giving rise to the idea of the Urban Digital Twin (UDT).

An Urban Digital Twin is far more than a static three-dimensional model of a city. Instead, it functions as a comprehensive digital platform that integrates large volumes of multi-source and heterogeneous urban data. By combining technologies such as the Internet of Things (IoT), cloud computing, big data analytics, and artificial intelligence, an urban digital twin enables real-time mapping, dynamic interaction, and continuous feedback between the physical city and its virtual counterpart [9,17].

In practical applications, urban digital twins have already demonstrated significant transformative potential. For example, in intelligent transportation systems, digital twin platforms can simulate real-time traffic conditions, predict congestion patterns, and dynamically adjust signal timing strategies. In emergency management, they can model the spread of disasters such as fires or floods and assist decision-makers in designing effective evacuation routes and rescue strategies [10].

In the field of urban planning and design, digital twins provide an entirely new technical approach for addressing the limitations of traditional planning methods. Their capabilities in dynamic simulation, multi-scenario prediction, and collaborative decision-making allow planners to test different urban design proposals within a virtual environment. Through this process, planners can evaluate how variations in building layout, land use structure, or policy interventions might influence factors such as urban wind patterns, sunlight exposure, noise conditions, thermal environments, transportation systems, and energy consumption [18].

By identifying potential problems and quantitatively comparing alternative strategies before they are implemented, digital twin platforms help planners make more informed and forward-looking decisions. This emerging paradigm—often described as “simulating in the digital world before implementing in the physical world”—greatly enhances the scientific rigor, efficiency, and transparency of urban planning processes while supporting the broader goal of evidence-based planning.

C. Quantitative Assessment Methods for Blue-Green Space Exposure

To translate the health benefits of blue-green spaces into practical planning and design indicators, it is essential to measure residents’ exposure to these environments in a scientific and reliable way. As noted earlier, two key physical dimensions are commonly used to describe such exposure: spatial accessibility and spatial visibility. Researchers have developed a range of quantitative methods to evaluate these dimensions.

1) For spatial accessibility, assessment methods generally fall into three main categories.

The first category is the statistical indicator method, which evaluates green space supply by calculating indicators such as total green space area, per capita green space area, or green space coverage rate within a defined geographic unit, such as an administrative district or community. Although this method is straightforward and easy to implement, it does not consider actual travel distances or mobility constraints [7].

The second category is the spatial proximity method, which measures the distance or travel cost from a demand point—such as a residential location—to the nearest entrance of a blue-green space. This cost can be calculated using simple Euclidean distance, more realistic network distance along streets, or estimated travel time. In recent years, the use of online mapping service APIs (such as the Google Maps API) has enabled researchers to incorporate real-time travel conditions and transportation modes, thereby improving the accuracy of accessibility measurements [19].

The third category is the spatial interaction method, which provides a more comprehensive evaluation by simultaneously considering the supply of blue-green spaces (their size and quality), population demand, and the spatial resistance between them. Among these approaches, the Two-Step Floating Catchment Area (2SFCA) method and its improved variants, such as the Gaussian 2SFCA (G2SFCA), are widely used. These models generate accessibility scores for each demand location, making it possible to identify service gaps and evaluate the spatial equity of green space distribution [20].

2) In terms of spatial visibility, several analytical methods have also been developed.

The traditional Viewshed Analysis method is typically performed within a GIS environment. Using a Digital Elevation Model (DEM) or Digital Surface Model (DSM), it calculates the areas of blue-green space that are visible from specific viewpoints or along certain paths. This method is often applied in large-scale visual impact assessments [7]. However, approaches based on 2.5D raster data have limitations when representing complex three-dimensional urban forms.

To address this limitation, Isovist Analysis based on three-dimensional models has become increasingly popular. Isovist analysis calculates the entire visible area from a given viewpoint within a 3D scene and generates various morphological indicators, such as visible area size, perimeter, and spatial openness. These metrics provide powerful tools for evaluating visual experiences at the street or neighborhood scale [21].

More recently, advances in computer vision and deep learning have introduced image-based methods for visibility assessment. Through semantic segmentation of street-view images or on-site photographs, these techniques automatically identify and classify landscape elements such as sky, buildings, vegetation, and water bodies. The pixel proportions of each category can then be calculated, allowing researchers to quantitatively measure the visible share of blue-green elements, visual complexity, and environmental naturalness at large scales and with high precision [22].

D. *Research Review and Theoretical Gaps*

Taken together, the literature on healthy cities, digital twin technology, and blue-green space evaluation provides a solid theoretical and technical foundation for this research. However, there remains a clear gap in integrating these three domains into a coherent methodological framework for health-oriented blue-green network planning and design.

First, current applications of digital twin technology in urban studies have primarily focused on " gray infrastructure, " such as transportation networks, buildings, and utility systems. Research exploring how digital twins can support the simulation and optimization of ecological infrastructure, including blue-green networks, is still relatively limited.

Second, although many analytical methods exist for evaluating blue-green spaces, they are often used in fragmented ways. Different studies employ different spatial scales and methodological approaches, making it difficult to compare results or integrate findings. In particular, there is a lack of a unified framework capable of coordinating multi-scale and multi-dimensional analyses. For example, regional accessibility analyses may identify general spatial patterns but offer limited guidance for detailed street-level design. Similarly, optimization strategies that focus only on accessibility while ignoring visibility may fail to deliver meaningful improvements in residents ' real-world health experiences.

Finally, much of the existing research focuses primarily on assessment of current conditions. There is still limited work on how evaluation results can be translated into specific, actionable spatial optimization strategies, or how digital twin platforms can be used to simulate and iteratively refine these strategies before implementation.

Therefore, the key contribution and necessity of this study lie in its attempt to develop a comprehensive framework based on digital twin technology, with the explicit goal of enhancing residents ' health benefits through improved blue-green networks. Rather than simply combining multiple technologies, the study seeks to establish a data-driven and dynamically interactive planning paradigm.

Through this framework, the research aims to bridge the gap between macro-level strategic planning and micro-scale environmental design, while also connecting the two critical dimensions of spatial accessibility and visual perception. Ultimately, the goal is to maximize the health benefits provided by urban blue-green networks and to offer planners and policymakers a scientifically grounded, precise, and practical methodological toolkit for advancing the development of truly healthy cities.

III. METHODOLOGY

To enable a systematic evaluation and optimization of the health benefits provided by urban blue-green networks, this study develops a digital twin–driven multi-scale analytical framework. The framework follows a structured "data–model–analysis–optimization" workflow, forming an iterative decision-support process that can be reproduced under typical research conditions. Rather than relying on a fully instrumented, real-time urban digital twin, the study constructs an open-data, model-based digital twin environment by integrating publicly available spatial datasets. When certain data are unavailable, clearly defined proxy variables are introduced to maintain analytical continuity. This digital twin environment provides a unified spatial foundation that supports all subsequent analyses.

Within this framework, a series of quantitative models are applied to evaluate the core health-related performance of the urban blue-green network, focusing on two key dimensions: spatial accessibility and spatial visibility. These indicators are examined across three spatial scales—regional, district, and local—allowing the study to capture both macro-level spatial patterns and fine-grained environmental experiences. Through this multi-scale analytical process, the framework can reveal structural weaknesses, spatial inequalities, and service gaps within the existing blue-green network.

Finally, based on the results of these evaluations, the study identifies critical problem areas and proposes coordinated optimization strategies aimed at improving both accessibility and visual exposure to blue-green spaces. These strategies are tested and refined within the digital twin environment, enabling planners to simulate potential outcomes before implementation. In this way, the framework provides a data-driven and evidence-based decision-support tool for urban planning and design, helping cities develop more equitable, accessible, and health-promoting blue-green infrastructure systems.

A. *Overall Research Framework*

The technical route of this study follows a systematic process (see Figure 1).

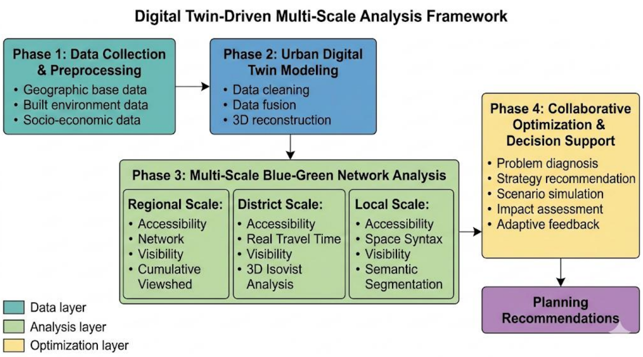

Fig. 1. Research Framework Flowchart

The first step of the framework involves data collection and preprocessing, which focuses on gathering essential geographic information, built environment data, and socio-economic datasets from open platforms or routine planning archives. These datasets provide the foundational information required for subsequent analysis.

The second step is urban digital twin modeling. In this stage, the collected data are cleaned, harmonized, and structured into a consistent 2D, 2.5D, and 3D analytical environment that can be reproduced offline. When detailed three-dimensional data are unavailable, simplified representations are adopted, accompanied by sensitivity analyses to maintain transparency and methodological reliability.

The third step is the multi-scale analysis of the blue-green network, which represents the core component of this research. Within the digital twin environment, the study evaluates spatial accessibility and spatial visibility at three levels — macro, meso, and micro — allowing for a comprehensive understanding of the performance of blue-green infrastructure across different spatial scales.

The fourth step focuses on collaborative optimization and decision support. By integrating the results from the multi-scale analyses, the framework diagnoses both the strengths and weaknesses of the existing blue-green network system. Based on these insights, targeted spatial intervention strategies are proposed to support evidence-based urban planning and design decisions.

B. Urban Digital Twin Model Construction

A high-fidelity and multi-dimensional urban digital twin model forms the foundation of this research framework. Its construction relies on integrating multiple sources of heterogeneous data, which can be broadly categorized into three groups.

1) Basic Geographic Information Data

These datasets provide the structural basis of the city's spatial framework. They typically include vector-format road networks, water systems (such as rivers and lakes), and green space patches, which can be obtained from open platforms such as OpenStreetMap or from local surveying and mapping departments. Together, these datasets define the spatial pattern and connectivity of the urban blue-green network.

2) Built Environment Data

Built environment data describe the city's physical form and are primarily used for visibility-related analyses. To maintain a feasible and reproducible workflow, this study prioritizes publicly available building footprint data and height proxies, which may be derived from remote sensing products. When available, a Digital Surface Model (DSM) is also incorporated.

If detailed height information—such as LiDAR-derived building heights — is unavailable, simplified height assignment rules based on land-use categories or building-type classifications are applied. Sensitivity analyses are then conducted to evaluate how uncertainty in height data may affect the results. This approach allows visibility analysis to be performed without relying on costly or difficult-to-reproduce datasets.

3) Socio-economic Data

Socio-economic datasets represent the population distribution and activity patterns within the city. These mainly include gridded population datasets released by statistical agencies and Points of Interest (POI) data obtained from online map services. POI categories typically include residential areas, workplaces, schools, hospitals, and other activity locations. These data provide the basis for defining demand points in accessibility assessments.

After data collection, several preprocessing procedures are carried out, including coordinate system standardization, topology correction, data cleaning, and attribute integration. The processed datasets are then incorporated into a unified GIS database and 3D spatial environment, forming a comprehensive digital twin model that represents the city's physical structure, spatial relationships, and population distribution.

C. Multi-Scale Analysis Model of the Blue-Green Network

To fully understand the performance of the blue-green network, this study adopts a cross-scale analytical strategy. Different spatial scales reveal different types of problems and correspond to different intervention approaches. The framework therefore integrates multiple analytical models across regional, district, and local levels.

1) Regional Scale Analysis

At the macro city scale, the focus is on the overall spatial pattern and equity of blue-green resource distribution.

a) Accessibility Assessment

The Gaussian Two-Step Floating Catchment Area (G2SFCA) method is employed. The city is first divided into a uniform grid. Each blue-green space patch is treated as a service center, and its service capacity is calculated based on its area and a distance-decay function modeled using a Gaussian distribution.

Next, each residential population grid searches for all blue-green spaces within its service radius. The service capacities of these spaces are then weighted and aggregated to produce an accessibility score for each population grid. This method considers supply, demand, and spatial impedance simultaneously, enabling the identification of citywide accessibility hotspots and service gaps.

b) Visibility Assessment

A Cumulative Viewshed Analysis is conducted using the Digital Surface Model (DSM). Observation points are placed along major road networks and public open spaces. From these points, the visible areas of major blue-green features—such as large parks and water bodies—are calculated. By overlaying visibility results across all observation points, a blue-green landscape visibility heat map can be generated, revealing areas of the city with stronger or weaker visual access to natural landscapes.

2) District Scale Analysis

At the meso scale — typically corresponding to neighborhoods or community districts—the analysis focuses on residents' daily interaction with nearby blue-green spaces.

a) Accessibility Assessment

A network-based accessibility approach is used to ensure transparency and reproducibility. Instead of relying on paid or time-variable online mapping APIs, the analysis calculates shortest-path distances and estimated travel times along an open-source road network dataset. Fixed walking or cycling speeds are applied to convert distance into travel time.

This method captures the influence of street connectivity, barriers, and crossing constraints while maintaining methodological transparency. When travel times from external APIs are available, they can serve as an optional validation layer rather than a required data source [19].

b) Visibility Assessment

Visibility along main streets and pedestrian corridors is analyzed using a 2.5D line-of-sight and viewshed approach based on the DSM. Observation points are sampled at regular intervals along selected routes. From each point, visibility indicators are calculated to identify visually open segments and visual bottlenecks within the urban landscape.

When detailed 3D city models are available, 3D Isovist analysis can be incorporated as an optional enhancement. This method generates additional indicators—such as visible area and spatial openness — that support more refined modeling of pedestrian visual experiences [21].

3) Local Scale Analysis

At the micro scale, such as individual blocks or street segments, the analysis examines how specific design elements influence the accessibility and visual quality of nearby blue-green spaces.

a) Accessibility Assessment

The study applies Space Syntax analysis to model the axial lines of the local street network. Two key indicators are calculated: Integration and Choice.

Streets with high integration are easier to reach from other parts of the network and tend to attract more movement.

Streets with high choice serve as important through-routes within the network.

By examining the syntactic values of streets that connect to blue-green space entrances, the analysis evaluates their structural accessibility and visibility within the street network.

b) Visibility Assessment

At the local scale, image-based visual composition analysis is applied. For selected viewpoints — such as park entrances or major street intersections — the proportions of landscape elements (including sky, buildings, roads, vegetation, and water) are measured.

Where publicly available imagery exists, semantic segmentation models such as FCN-8s or comparable open-source implementations can be used to automatically classify landscape components. To ensure reproducibility, model versions, parameters, and sampling procedures are fully documented [22].

When imagery coverage is limited, a simplified manual or rule-based labeling process can be used instead. This ensures consistent evaluation while keeping the workflow feasible under typical research conditions.

D. Collaborative Optimization Strategies

The purpose of this framework is not only to evaluate existing conditions but also to guide practical optimization strategies. Based on the results of the multi-scale analysis, a collaborative optimization decision-support matrix is developed.

This matrix links identified problems at different spatial scales — such as regional accessibility gaps, district-level visual barriers, or local street network limitations — with corresponding spatial intervention strategies.

1) Examples include:

Regional scale: constructing new community parks or pocket parks in areas identified as accessibility service gaps.

District scale: improving pedestrian connectivity by opening blocked routes, adding pedestrian bridges, or enhancing pathway continuity.

Local scale: improving the visibility and accessibility of park entrances by adjusting building setbacks, removing boundary walls, or redesigning streetscapes.

Within the digital twin platform, planners can virtually implement these strategies and rerun the analytical models to evaluate potential outcomes. By comparing the effects of different intervention scenarios, decision-makers can identify the optimal strategy combination that balances cost, spatial equity, and public health benefits.

In this way, the framework provides a powerful tool for supporting data-driven urban renewal, planning, and design, helping cities develop more accessible, visible, and health-promoting blue-green infrastructure systems.

IV. CASE STUDY AND RESULTS

To evaluate the effectiveness and practical applicability of the digital twin – driven analytical framework proposed in this study, a case study was conducted in "Lincheng," a rapidly urbanizing coastal city in eastern China. By applying the multi-scale analytical approach to Lincheng's digital twin model, the study systematically assessed the health-related performance of the city's blue-green network and identified key opportunities for spatial optimization.

A. Study Area Profile

Lincheng is a megacity with a population exceeding eight million and exhibits a typical multi-core, cluster-based urban development pattern. The historic urban center has developed along both banks of the Yong River, forming a dense built-up area with a long development history and high building density. Surrounding this core are newly developed districts that include emerging central business districts (CBDs), large residential communities, industrial parks, and several freshwater lakes.

The city's complex spatial structure, diverse blue-green resource types, and noticeable socio-economic spatial disparities make it an ideal case for testing the multi-scale analytical framework proposed in this study. Using the methods described earlier, we integrated multiple datasets—including remote sensing imagery, building vector data, road network data, census grid data, and Points of Interest (POI) information — to construct a high-resolution urban digital twin model of Lincheng. This model provides a unified spatial data environment that supports all subsequent analyses.

B. Regional Scale Analysis Results

At the macro city scale, the analysis focuses on evaluating the overall spatial pattern and equity of blue-green infrastructure distribution.

First, the Gaussian Two-Step Floating Catchment Area (G2SFCA) method was applied to evaluate the accessibility of blue-green spaces across the entire city. As illustrated in Figure 2, the results show a clear pattern of spatial differentiation.

1) Accessibility Assessment (Based on the G2SFCA Model).

In the visualization, warmer colors represent higher accessibility, while cooler colors indicate lower accessibility levels. Areas with the highest accessibility—referred to as "hotspots" —are mainly concentrated in the central urban area along the Yong River and the southern new city district, where several large lake parks are located. Residents in these areas benefit from convenient access to high-quality blue-green spaces.

However, the analysis also reveals several large "cold spots" with low accessibility, indicating significant service gaps in the blue-green network. These areas are primarily located in two regions:

- Northern and western districts, where many old industrial areas and urban villages are located. In these areas, historical green space provision is limited in both number and scale, and the complex road network structure further restricts residents' access to nearby parks.
- Emerging development zones in the eastern suburbs, where large green spaces have been planned but remain poorly connected to surrounding residential areas due to insufficient transportation and pedestrian infrastructure.

These findings highlight a clear spatial inequality in the distribution and accessibility of blue-green infrastructure across the city.

Following the accessibility analysis, a cumulative viewshed analysis was conducted to evaluate the visibility of blue-green landscapes throughout the city. As shown in Figure 3, areas with the highest visibility are largely concentrated in open spaces along the Yong River waterfront and around several major urban lakes.

In the visualization, redder areas indicate higher frequencies or larger visible areas of blue-green landscapes. Large water bodies and extensive green spaces form the city's primary visual landmarks and landscape focal points.

Nevertheless, the analysis also reveals a notable issue in the central business district (CBD). Although the CBD is located near the waterfront and enjoys a prime geographic position, the dense clusters of high-rise buildings create a "concrete canyon" effect, significantly blocking sightlines from interior streets toward the riverfront and surrounding green areas. This results in extensive visual occlusion zones.

These findings suggest that proximity to blue-green spaces alone does not guarantee that residents can benefit from their visual and psychological advantages. The control of building height, density, and urban form therefore plays a critical role in preserving and creating urban visual corridors that allow natural landscapes to remain visible within dense urban environments.

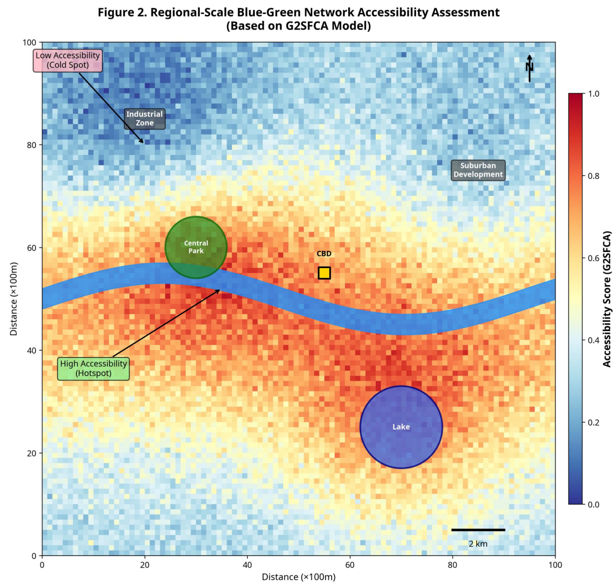

Fig. 2. Regional-Scale Blue-Green Network

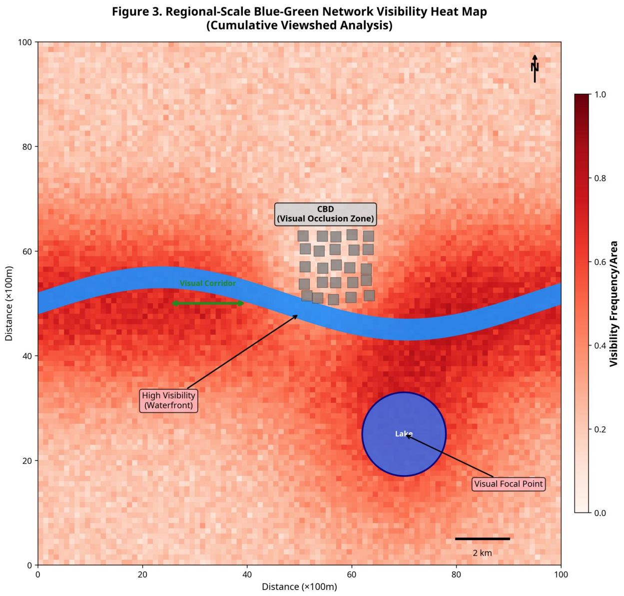

Fig. 3. Regional-Scale Blue-Green Network Visibility Heat Map.

C. District Scale Analysis Results

To better understand residents' everyday experiences at the meso (district) scale, the study selected the Xinyue area as a representative case. Xinyue is located in the city center and features a mixed urban environment that includes high-density residential neighborhoods, commercial office buildings, and waterfront leisure spaces. A canal runs through the district, with several residential compounds and office complexes distributed along both sides, making it a suitable setting for examining the interaction between urban residents and nearby blue-green spaces.

Using a reproducible network-based analysis built on an open road network dataset, we calculated the number of blue-green space entrances reachable within a 10-minute walking distance from each building in the area. The analysis applied clearly defined walking speeds and network impedance rules to ensure transparency and reproducibility (Figure 4).

In the resulting map, darker colors indicate a greater number of accessible blue-green space entrances within a 10-minute walking radius. Although the district contains a relatively large amount of blue-green resources overall, their effective accessibility is highly uneven. Buildings located directly along the canal or next to park entrances show very high walking accessibility, allowing residents to reach multiple blue-green spaces within a short distance.

However, several nearby residential communities — sometimes located just one street away from the canal or park areas — experience dramatically lower accessibility. This is mainly due to urban barriers such as major arterial roads, gated residential compounds, and dead-end streets, which interrupt pedestrian connectivity. As a result, residents in these areas may find it nearly impossible to reach a blue-green space entrance within a 10-minute walk, creating a paradoxical situation where natural amenities are geographically close but functionally inaccessible.

This finding highlights that at the district scale, improving pedestrian micro-connectivity and street permeability is essential for optimizing the accessibility of blue-green networks. Measures such as opening blocked pathways, introducing mid-block pedestrian connections, and improving crossing facilities can significantly enhance residents' ability to access nearby blue-green spaces.

For the visibility analysis, we examined the dynamic visual experience of pedestrians walking along a major riverside promenade in the district. A sequence of viewshed and line-of-sight – based indicators was sampled continuously along the promenade route. Based on these samples, we generated a curve showing how the proportion of visible blue-green elements (water and vegetation) changes along the walking path (Figure 5).

The curve represents fluctuations in the percentage of blue-green elements within the pedestrian's field of view. The results demonstrate that the visual experience of pedestrians along the waterfront is highly dynamic rather than uniform.

At certain open spatial nodes, such as Point A in Figure 5 (a waterfront plaza), the visible proportion of blue-green elements exceeds 60%, providing pedestrians with a strong visual connection to natural landscapes and creating an enjoyable spatial experience.

In contrast, other sections—such as Point B in Figure 5—show a dramatic drop in visibility. Here, tall buildings, advertising billboards, or poorly positioned street trees obstruct the visual corridor, reducing the visible proportion of blue-green elements to below 10%. These locations effectively form "visual bottlenecks," interrupting the continuity of the waterfront landscape experience.

This type of fine-grained dynamic analysis provides valuable quantitative evidence for micro-scale urban design decisions. It can inform the placement and design of street furniture, building setback regulations, vegetation layering, and landscape corridors, helping planners create streets and promenades that maintain continuous visual connections to nearby blue-green spaces.

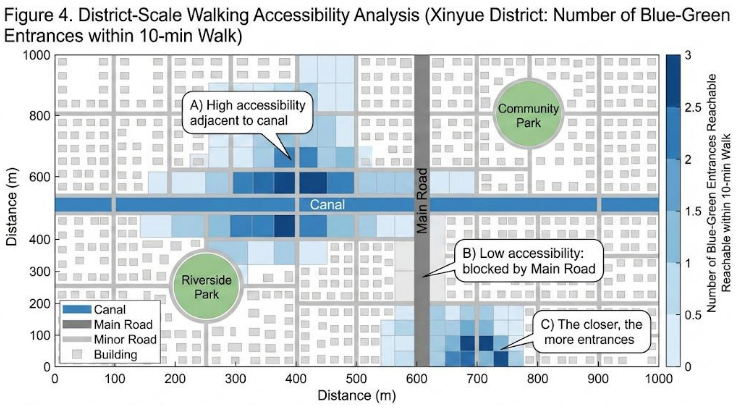

Fig. 4. District-Scale Walking Accessibility Analysis in Xinyue District.

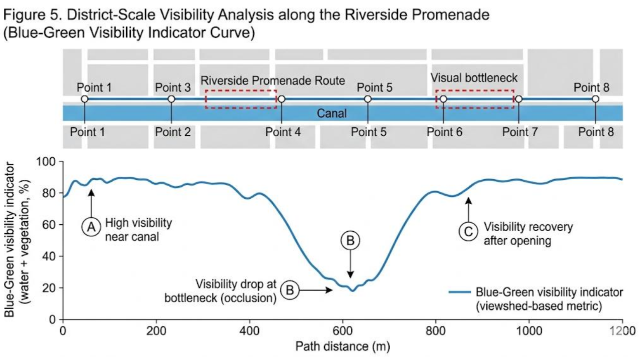

Fig. 5. Dynamic Visibility Analysis along the Xinyue District Riverside Promenade.

D. Local Scale Analysis Results

Finally, the analysis was further refined to the micro scale of streets and individual plots in order to diagnose specific design problems within the built environment. The main entrance of a large urban park in the Xinyue district was selected as the focal case for this level of analysis.

The results of the Space Syntax analysis (Figure 6) indicate that although the street where the park entrance is located appears geographically central, its Integration value within the overall road network is only at a medium – low level.

Figure 6. Space Syntax Integration Analysis of the Local Road Network around the Park Entrance

In the visualization, warmer colors represent higher integration values and stronger accessibility potential. Streets with higher integration tend to attract more pedestrian movement because they are easier to reach from other parts of the network. In contrast, the street hosting the park entrance shows relatively low integration, meaning it is not naturally positioned as a route that people frequently pass through or linger in unless they have a specific destination. Consequently, its potential to attract spontaneous pedestrian flow is limited.

This finding helps explain why the park — despite its considerable size and environmental value — has relatively low visitor activity near the main entrance. Improving the situation therefore requires more than simply enhancing the physical entrance design. It also involves strengthening the topological connectivity of the street within the broader urban spatial network. Possible interventions include reinforcing connections between this street and nearby high-integration streets, creating more direct pedestrian links, and improving route legibility to help guide pedestrian flows toward the park.

In addition to the accessibility analysis, we conducted an image-based visual composition assessment of a representative street-level view looking outward from the park ' s main entrance. The analysis quantifies the visual proportions of different landscape elements in the scene using a reproducible evaluation protocol that specifies viewpoint selection, image source, and calculation procedures.

The resulting pie chart illustrates the pixel proportions of major landscape elements within the field of view. The results show that built elements dominate the visual scene, while natural elements—such as vegetation and sky—occupy a significantly smaller share.

Specifically, tall commercial building facades, visually cluttered shop signage, and overly dense street trees combine to create a narrow and enclosed street canyon effect. This spatial condition diminishes the visual openness of the entrance area and weakens the perceptual role of the park as an urban "green lung."

These findings highlight that at the local design scale, improving the interface between blue-green spaces and the surrounding city requires integrated and fine-grained spatial design strategies. Adjustments to building frontage design, street proportions, vegetation arrangement, and visual corridors can significantly improve the spatial transition between dense urban environments and natural landscapes, ultimately creating healthier and more welcoming entry environments for urban blue-green spaces.

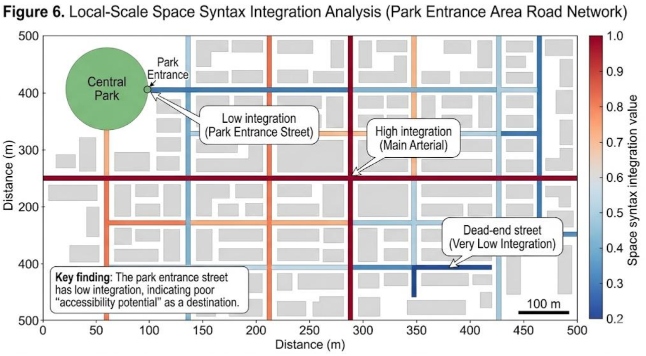

Fig. 6. Space Syntax Integration Analysis of the Park Entrance Local Road Network.

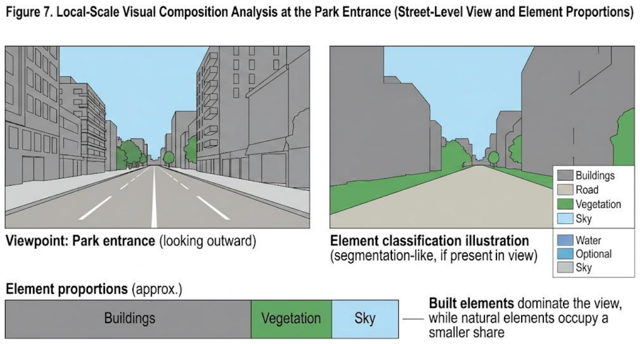

Fig. 7. Semantic Segmentation Results of the View from the Park's Main Entrance.

V. Discussion

By applying the multi-scale analytical framework to the digital twin model of Lincheng, this study systematically evaluated the spatial accessibility and visibility of the city' s blue-green network. The findings not only reveal the current strengths and weaknesses of Lincheng ' s blue-green infrastructure in delivering health benefits but also demonstrate the potential of the proposed framework as a practical decision-support tool for urban planning and design. This section further interprets the results and discusses their implications for methodology, planning practice, and future research.

A. Interpretation and Integration of Results

One of the most important findings of this research is that the health performance of urban blue-green networks shows clear scale dependence and dimensional variation.

At the regional scale, the large-scale ecological structure formed by major parks and water bodies largely determines the basic spatial pattern of accessibility and visibility. In Lincheng, this creates a typical " core – periphery " structure, where areas along the Yong River and around major lakes exhibit significantly higher accessibility and visual exposure to blue-green spaces.

However, when the analysis moves to the district scale, the results reveal that favorable macro patterns do not automatically translate into real accessibility for residents. Factors such as micro-level road connectivity, the quality of the walking environment, and the presence of physical or psychological barriers become decisive in determining whether people can actually reach nearby blue-green spaces. Even when these resources are geographically close, poor pedestrian connectivity may prevent residents from benefiting from them.

At the local scale, the analysis further shows that physical proximity alone does not guarantee active use of blue-green spaces. The topological accessibility of streets, as revealed through space syntax analysis, and the visual quality of the surrounding built environment both influence how attractive and accessible these spaces feel to users. Elements such as building height, street enclosure, signage clutter, and vegetation arrangement can significantly affect people ' s perception of openness and comfort.

Together, these cross-scale findings challenge traditional planning approaches that rely on single-scale or single-indicator assessments, such as green space ratio or per capita park area. Instead, the results highlight the need for systematic optimization across the entire chain of urban space, from macro ecological structure to meso-level connectivity and micro-scale spatial experience.

Another key finding is the mismatch between accessibility and visibility. The study shows that areas with high accessibility are not always areas with strong visual exposure to blue-green landscapes. A typical example is the central business district, where waterfront spaces are physically close and relatively easy to reach but are visually blocked by dense clusters of high-rise buildings.

This finding carries important planning implications: blue-green network optimization must simultaneously consider both accessibility and visibility. Simply increasing the number of parks or improving their proximity may not fully realize their health benefits if visual corridors toward natural landscapes are blocked. By integrating 3D spatial analysis with image-based visual perception evaluation, the digital twin framework developed in this study provides a powerful tool for addressing these two dimensions simultaneously.

B. Methodological Implications

This research contributes several methodological innovations to the study of healthy cities and urban planning.

First, it proposes a digital twin – based paradigm for evaluating blue-green networks. Compared with conventional GIS-based static analyses, the digital twin framework integrates multi-source and multi-dimensional urban data within a unified analytical environment. More importantly, it enables interactive scenario simulation, allowing planners to test different spatial intervention strategies before implementation.

Through this approach, the planning process shifts from producing a single static blueprint to a more iterative, evidence-based decision-making process. Planners can evaluate the potential impacts of different design options and refine strategies based on simulated outcomes.

Second, the study establishes a comprehensive analytical toolkit that integrates multiple models across different spatial scales and disciplines. The framework combines:

- G2SFCA models from spatial geography for accessibility evaluation
- Space Syntax analysis from urban morphology for street network structure
- Semantic segmentation techniques from computer vision for visual perception assessment

This cross-disciplinary integration overcomes the limitations of relying on a single analytical method and provides a more holistic understanding of the interactions between residents and urban blue-green environments. At the same time, the workflow remains replicable and scalable, offering a methodological reference that can be adapted for use in other cities.

C. Planning and Design Implications

The findings of this study provide several practical insights for healthy city planning and design.

1) From “Quantity” to “Quality and Equity”

At the regional scale, urban planning should move beyond simply increasing the amount of green space. Instead, greater emphasis should be placed on the equitable spatial distribution of blue-green resources. Models such as G2SFCA can help planners identify underserved areas and guide the targeted development of new parks or community green spaces, ensuring that all residents benefit from urban ecological resources.

2) Bridging the “Last Mile” of the Pedestrian Network

At the district scale, improving pedestrian connectivity and walkability is essential. The analysis of travel distance and walking time highlights the importance of removing barriers such as gated communities, disconnected street networks, and inaccessible crossings. Interventions such as opening pedestrian pathways, introducing bridges or underpasses, and improving street design can significantly enhance residents’ ability to reach nearby blue-green spaces.

3) Integrating “Green Lungs” with “Urban Canyons”

At the local scale, design strategies should emphasize the integration of blue-green spaces with the surrounding built environment. The results from space syntax and visual analysis indicate that park entrances function not only as physical access points but also as important nodes within the urban spatial network and key visual interfaces.

Effective design strategies may include:

- Strengthening connections between park entrances and highly integrated streets
- Adjusting building heights and setbacks to maintain visual corridors
- Redesigning facades and street interfaces to create open, welcoming environments
- Coordinating vegetation layers and landscape elements to improve spatial perception

These measures can transform park entrances into inviting transition spaces between dense urban environments and natural landscapes.

D. Limitations and Future Research

Although this study provides several valuable insights, some limitations remain and offer directions for future work.

First, the digital twin environment used in this study is primarily based on static or periodically updated datasets. As a result, it does not explicitly capture short-term variations such as time-of-day changes in mobility patterns or temporary fluctuations in urban activity. Future research could incorporate open mobility datasets, aggregated movement statistics, or low-cost sampling approaches to evaluate the temporal robustness of blue-green accessibility. Real-time sensing through IoT devices could also be explored as an optional enhancement.

Second, the current evaluation of health benefits focuses mainly on physical environmental indicators, particularly accessibility and visibility. While these indicators are strongly linked to health outcomes, the study does not directly measure physiological or psychological responses among residents. Future studies may integrate survey-based approaches, open health statistics, or behavioral data to better understand the relationship between environmental exposure and health outcomes. Wearable sensor technologies could also be considered where resources permit.

Finally, the optimization strategies proposed in this research remain largely conceptual. Future work could integrate automated optimization algorithms, such as genetic algorithms or multi-objective optimization models, within the digital twin platform. Such methods could automatically generate and evaluate numerous planning scenarios, further improving the efficiency, rigor, and scientific basis of urban planning decision-making.

Overall, this study demonstrates how a digital twin – driven, multi-scale analytical framework can deepen our understanding of the complex relationships between urban form, blue-green infrastructure, and public health. By bridging macro-level planning strategies and micro-scale design interventions, the framework offers a promising pathway for developing more equitable, accessible, and health-supportive urban environments.

VI. Conclusion

In the broader effort to build healthy cities, maximizing the health benefits of urban blue-green networks has become an increasingly important challenge. Addressing this issue, the present study develops a digital twin – driven multi-scale analysis and optimization framework that integrates Geographic Information Systems (GIS), Space Syntax, and computer vision techniques. Through this integrated approach, the framework systematically evaluates the accessibility and visibility of urban blue-green infrastructure and provides a structured basis for planning interventions. The case study conducted in Lincheng demonstrates that the framework can effectively diagnose the performance of blue-green networks across multiple spatial scales, identify critical deficiencies, and support the formulation of targeted optimization strategies.

This study makes three main contributions:

- First, from a theoretical perspective, it advances research on the health benefits of blue-green spaces by proposing a comprehensive analytical framework that explicitly accounts for both scale dependence and dimensional differences. By linking regional ecological structures with district-level connectivity and local design conditions, the framework helps bridge the long-standing gap between macro-level planning strategies and micro-scale spatial design.
- Second, from a methodological perspective, the research introduces a new paradigm for urban planning studies based on digital twin technology. The proposed framework demonstrates how multi-source urban data and interdisciplinary analytical tools can be combined within a unified digital environment. This approach offers a replicable and scalable technical pathway for conducting fine-grained assessments and optimization of urban ecological systems.
- Third, from a practical perspective, the framework provides urban planners and managers with a scientific, quantitative, and interactive decision-support tool. By enabling planners to evaluate spatial performance, simulate intervention scenarios, and compare potential outcomes, the framework supports the development of more equitable, accessible, and perceptible blue-green infrastructure systems, thereby contributing to healthier urban environments.

As digital twin technologies continue to evolve and urban data resources become increasingly accessible, the data-driven, simulation-based, and collaboratively optimized planning paradigm demonstrated in this study is expected to play a growing role in addressing complex urban challenges. By enabling planners to better understand and manage the relationships between urban form, ecological systems, and human well-being, such approaches will help promote more sustainable, resilient, and livable cities.

Overall, this research represents a meaningful step toward that goal. It aims to encourage further interdisciplinary exploration and contribute to the development of urban environments that are not only more efficient and sustainable but also healthier and more enjoyable places to live.

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AUTHOR CONTRIBUTIONS

Praphan Intara: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing—original draft.

Haiqiao Huang: Resources, Validation, Supervision, Writing—review & editing, Project administration.

COMPETING INTERESTS

The authors declare no competing interests.