



OPTIMIZING URBAN NATURE-BASED SOLUTIONS THROUGH ARTIFICIAL INTELLIGENCE: PROSPECTS FOR THE CITY OF NIŠ

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Abstract

Modern smart city concepts are evolving from techno-centric models focused on raw data collection toward ecologically sustainable urban ecosystems. The primary challenge of contemporary urbanism lies in mitigating climate change impacts, particularly the urban heat island (UHI) effect and air quality degradation. This paper explores the potentials of optimizing urban Nature-based Solutions (NbS) and green infrastructure through Artificial Intelligence (AI) and Urban Digital Twins (UDT) as advanced analytical tools. A theoretical framework is established by integrating concepts of intelligent Nature-based Solutions, IoT-based environmental monitoring, digital twin technologies, and generative urban design. Through a comparative analysis of global best practices -specifically Barcelona, Helsinki, and Vienna, the research identifies how AI-supported decision-making can improve environmental monitoring, optimize green infrastructure placement, enhance mobility management, and increase the efficiency of municipal services. The second part of the paper focuses on highlighting the prospective opportunities and open possibilities for the city of Niš, exploring how these global methodologies could address critical local issues such as summer thermal stress and winter air pollution. Rather than proposing an immediately deployable technological solution, the paper develops a conceptual framework for the gradual introduction of AI-assisted ecological planning adapted to local institutional and infrastructural conditions. While a systematic institutional framework for AI urban implementation currently does not exist in the local context, this study highlights the importance of early-stage exploratory research. Such academic inquiry is essential for bridging theoretical data science and local urban planning practice, positioning AI strictly as an analytical assistant for ecological optimization rather than a replacement for human expertise.

Key words: Artificial Intelligence, Smart Cities, Nature-based Solutions, Digital Twin, Niš.

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1. INTRODUCTION

Accelerated urbanization and the climate crisis have created an urgent need to transform traditional cities into more resilient and sustainable systems. The first generation of smart cities was frequently criticized for technological determinism, where success was measured by the sheer volume of installed cameras, sensors, and free Wi-Fi zones [1]. However, the contemporary paradigm frames technology strictly as a tool, while the ultimate goal remains sustainability—cleaner air, reduced energy consumption, and an enhanced quality of life for citizens [2].

In this context, Nature-based Solutions (NbS) and green infrastructure are recognized as vital components for reducing urban vulnerability [3, 4, 5]. Integrating vegetation systems, green roofs, and urban forests directly impacts the mitigation of urban heat islands, stormwater management, and biodiversity preservation [3, 5]. Yet, traditional green infrastructure planning often suffers from a lack of empirical, real-time data, leading to the suboptimal placement of greenery.

The emergence of Artificial Intelligence (AI) and Urban Digital Twins (UDT) introduces entirely new capabilities [6, 7, 8]. AI enables the concurrent analysis of numerous variables, identifying hidden spatio-temporal patterns that elude human observation [1]. The objective of this paper is to analyze how these advanced tools can be leveraged to simulate and optimize ecological interventions, with a specific focus on prospective implementation possibilities in the city of Niš.

2. THEORETICAL FRAMEWORK AND METHODOLOGY

This section establishes a tripartite methodological framework that integrates urban ecology with computational design. It systematically links IoT-driven environmental monitoring, digital twin simulation techniques, and generative spatial optimization to form an adaptive matrix for smart urban planning [6].

2.1. The concept of intelligent Nature-based Solutions (INbS)

By bridging ecological engineering and information-communication technologies, the concept of Smart or Intelligent Nature-based Solutions emerges. In this model, green areas are no longer static spatial elements but dynamic systems monitored by a network of IoT sensors [7]. Sensors gather data regarding soil moisture, ambient temperature, and pollutant concentrations, enabling automated resource management (e.g., smart irrigation) and predictive maintenance of urban greenery.

2.2. Urban Digital Twin as a simulation laboratory

An Urban Digital Twin is a digital, working copy of a city or its subsystem, powered by real and continuous data streams [8]. Unlike static 3D models, a digital twin integrates infrastructure, traffic, microclimate, and greenery data into a unified analytical environment [9]. Its core value lies in the capacity to execute "What-if" scenarios.



Through machine learning, a digital twin can simulate the impacts of various urban planning decisions before any physical intervention occurs [6]. For example, planners can virtually route traffic or simulate multi-year tree canopy growth to evaluate their cumulative cooling effects and energy savings within a matter of minutes.

2.3. Generative urbanism and spatial optimization

Generative Design uses AI algorithms to explore thousands of spatial configurations based on predefined parameters [9, 10]. Planners input constraints such as parcel boundaries, traffic accessibility, and environmental standards. The algorithm then generates a spectrum of optimal solutions that balance ecological goals (e.g., maximizing solar exposure and greenery coverage) with structural parameters.

3. TRANSFERABLE PLANNING APPROACHES FROM EUROPEAN SMART CITY PRACTICE

This section reviews selected European smart city initiatives to identify planning approaches and AI-based methodologies that may inform future ecological planning in Niš. The selected cities are not intended as direct benchmarks, but as mature examples from which transferable principles can be adapted to local environmental and institutional conditions. The selected cities represent complementary and well-documented examples of AI-supported urban planning, illustrating different yet interconnected domains of smart urban development: Barcelona in environmental sensing and digital twins, Helsinki in AI-supported mobility management, and Vienna in predictive infrastructure management. Together, these examples provide transferable planning approaches that are particularly relevant to the environmental and institutional context of Niš.

3.1. AI-based planning approaches in Barcelona, Helsinki, and Vienna

Barcelona's model demonstrates the importance of open data architecture. Among other data, the Sentilo platform links temperature, noise, air quality, and parking occupancy data, allowing municipal services to coordinate interventions seamlessly [11]. Through its supercomputing digital twin, the city simulates pedestrian dynamics and maps micro-accessibility to support its "15-minute city" paradigm, preventing ecosystem fragmentation and urban decay by restructuring traffic into localized "Superblocks" [12].

In Helsinki, AI addresses traffic congestion by optimizing multimodal transport in real time through the Whim application and the Mobility-as-a-Service (MaaS) framework [13]. By accurately synchronizing public transit, micro-mobility, and shared fleets, the system increased public transit usage by 12% while reducing private car reliance by 9%. This synchronized transit minimizes dependence on private vehicles, freeing asphalt surfaces that can be repurposed into green micro-locations, urban parks, and permeable spaces.

Vienna utilizes predictive maintenance within its Smart City Wien strategy to prevent public utility failures [14]. By deploying acoustic and pressure sensors across its water and energy grids, machine learning algorithms can detect microscopic structural degradations up to three weeks before a potential rupture occurs. From a sustainable urban management perspective, this approach reduces unnecessary street excavation, lowers greenhouse gas emissions from heavy machinery, prevents clean water loss, and minimizes material waste.

Taken together, these examples illustrate that AI can support urban ecological planning at multiple scales—from neighborhood-level interventions and mobility management to city-wide infrastructure monitoring. Rather than relying on a single technological solution, successful implementation depends on integrating complementary digital tools that address different environmental challenges within a coherent planning framework.

Although these initiatives differ in their technological focus, they share a common planning philosophy: AI is employed not as an end in itself, but as a decision-support tool that enhances environmental performance, resource efficiency, and the long-term resilience of urban systems. This common perspective provides the conceptual basis for considering how similar planning principles could be adapted to different local contexts.

As a synthesis of these examples, Table 1 summarizes how different AI-based planning approaches translate technological capabilities into ecological and functional benefits, highlighting transferable principles that may inform future urban interventions.

Table 1. AI-Based Planning Approaches in Selected European Cities

City	Technological Platform / Model	Primary Ecological and Functional Benefit
Barcelona	<i>Sentilo</i> open platform & supercomputing digital twin	Pedestrian flow mapping and "15-minute city" optimization via Superblocks.
Helsinki	<i>Whim</i> application & MaaS (<i>Mobility-as-a-Service</i>) system	Synchronization of public transit, reducing private car usage by 9% and cutting CO2 emissions.
Vienna	<i>Smart City Wien</i> predictive maintenance sensor network	Early detection of microscopic damages in water supply and energy grids.

Despite their technological sophistication, the success of these cities does not primarily stem from AI itself, but from the integration of AI within coherent planning institutions, environmental policies, and long-term urban strategies. Technology alone does not create sustainable cities; rather, it enhances planners' and decision makers' capacity to implement evidence based interventions within a clear ecological and governance framework.

4. DISCUSSION: AN APPLICATION FRAMEWORK FOR THE CITY OF NIŠ

Building upon the transferable planning approaches discussed in the previous section, this chapter explores how AI-based methodologies could be adapted to the specific urban context of Niš. Rather than proposing a fully operational deployment scheme, it presents a conceptual framework that identifies priority application areas



and potential implementation pathways under existing local institutional and infrastructural conditions. Given the current capacities, implementing AI through pilot projects and localized interventions appears more realistic than the immediate development of a comprehensive city-wide Urban Digital Twin.

As an initial implementation step, pilot applications could focus on selected urban areas characterized by pronounced environmental challenges, including the central urban area, densely built residential neighborhoods affected by the urban heat island effect, and major traffic corridors with persistent congestion. The proposed framework would primarily rely on publicly available satellite imagery, municipal air quality monitoring data, traffic counts, GIS databases, and environmental sensor data where available. Its implementation would require interdisciplinary cooperation among the City Administration of Niš, relevant public utility companies, urban planning institutions, and academic and research organizations, including the University of Niš. Such a phased approach would enable the gradual validation of AI-supported planning methods before considering the future development of a comprehensive Urban Digital Twin.

This implementation pathway reflects the current institutional capacities while creating opportunities for future integration of environmental monitoring, spatial analytics, and AI-assisted decision support into everyday urban planning practice. In this way, the proposed framework is intended to serve not as a fixed technological model, but as a flexible planning concept that can gradually evolve in parallel with the development of local data infrastructure, institutional cooperation, and digital governance capacities.

4.1. AI- driven Nature-based Solutions placement against urban heat islands

During summer heat waves, highly sealed areas within the urban core and dense commercial zones of Niš experience substantial thermal stress due to the urban heat island effect, whereas peripheral green areas display significantly lower baseline temperatures. Training machine learning models on land surface temperature (LST) data derived from satellite imagery could assist planners in pinpointing precise thermal hotspots and micro-locations where green interventions would yield the highest environmental relief [15].

Instead of traditional, arbitrary landscaping, generative urbanism simulations could test how targeted green corridors, vertical greenery on public buildings, or localized pocket parks within the dense city center could potentially reduce local surface temperatures by approximately 2–3°C under favorable conditions. This data-driven approach theoretically optimizes ambient cooling, mitigates localized thermal stress, and reduces building energy consumption required for air conditioning during extreme heat waves.

Crucially, this computational approach is of significant value during the initial phases of urban planning, where predictive modeling can guide the allocation of land-use zones and the optimal distribution of public areas. Furthermore, this method serves as an essential tool in urban regeneration processes [16] within inherited, highly built-up environments. By simulating ecological thresholds beforehand, planners can prevent excessive construction density, control population concentration overgrowth, and

ensure that infrastructural re-development does not compromise the local microclimate.

4.2. Predictive air quality management and smart forestry

Winter seasons in Niš are heavily impacted by critical spikes in particulate matter ($PM_{2.5}$ and PM_{10}), particularly within high-density residential zones characterized by low aeration and a prevalence of individual heating units. Traditional monitoring networks provide only descriptive, historical records of pollution. By utilizing AI algorithms to synthesize historical emission patterns, real-time climate telemetry, and terrain topography, the city can transition to a predictive environmental model [17].

In terms of functional application, this framework is highly relevant for urban forestry management and local ecological zoning. Predicting severe pollution accumulation 24 hours in advance allows municipal authorities to optimize the operational scheduling of public infrastructure. More importantly, long-term predictive data allows urban planners to strategically locate and design multi-layered green buffer strips and specific tree-canopy structures that maximize the bio-filtration of airborne particulates. This approach embeds environmental analytics directly into municipal public health strategies, transforming static park planning into an active micro-climate defense system within endangered residential areas.

4.3. Ecological traffic optimization and green corridor integration

Primary traffic arteries and chronic congestion points across the urban matrix serve as major localized sources of greenhouse gases and acoustic pollution. Implementing AI-driven computer vision systems at strategic intersections presents an analytical opportunity to mitigate these footprints. By analyzing vehicle counts and queue lengths in real time, traffic signals can dynamically adjust green light phases based on actual volume, minimizing vehicle idling and reducing exhaust emissions directly at major bottlenecks [18].

In terms of urban design, this computational approach is invaluable for developing Sustainable Urban Mobility Plans (SUMPs) and planning linear green infrastructure. Real-time and predictive traffic load mapping provides planners with empirical data to justify the conversion of redundant asphalt surfaces into permeable green shoulders, linear parkways, and pedestrian zones. Instead of treating transport infrastructure as an ecological dead zone, AI analytics enable the seamless integration of transit networks with urban green corridors. This reduces the fragmentation of urban ecosystems and minimizes the ecological footprint of transport networks inside the inherited urban fabric.

4.4. The role of an Urban Digital Twin as an integrative core

The localized AI applications described above—thermal mapping, predictive air quality modeling, and traffic flow optimization—should not operate as isolated, fragmented software systems. Instead, the ultimate prospective goal for a city like Niš would be their gradual synthesis within a unified Urban Digital Twin (UDT) framework.



An Urban Digital Twin serves as the integrative computational core that merges real-time environmental telemetry with 3D spatial geometry [19].

In the context of nature-based solutions, this platform acts as an interactive simulation laboratory where cross-sectoral impacts can be analyzed simultaneously. For instance, instead of evaluating a traffic intervention solely by its impact on vehicle speed, the digital twin allows planners to instantly visualize how altering traffic patterns correlates with reductions in particulate matter concentrations and localized surface cooling within neighboring green pockets. This technological integration transforms urban planning from a reactive process based on static, historical records into a dynamic, predictive science capable of evaluating complex socio-ecological feedback loops before any physical resources are deployed.

4.5. Critical reflection on the local institutional framework

It is critical to emphasize that a systematic, institutional, or regulatory framework for the deployment of AI or Urban Digital Twins in urban planning and public utility management currently does not exist in Niš or at the national level. The concepts outlined above remain prospective, theoretical suggestions based on global engineering methodologies.

However, exploratory academic papers of this nature are highly significant for several reasons. First, they establish the necessary theoretical groundwork and bridge the gap between advanced data science and practical urban design. Second, they prevent techno-centric path-dependency by defining ecological and human-centric priorities *before* physical technology procurement begins. Finally, they demonstrate how localized academic research can lay the foundation for future data-driven policy, ensuring that upcoming smart-city initiatives are driven by rigorous scientific parameters rather than commercial technology trends.

5. SOCIO-TECHNICAL, INSTITUTIONAL LEGAL, AND ETHICAL CHALLENGES

Implementing AI-driven ecological urbanism is not merely a technological acquisition; it introduces profound governance and ethical complexities. To successfully ground these conceptual models in reality, several critical challenges must be addressed concurrently:

- **Data Quality and Institutional Fragmentation:** The predictive accuracy of any AI or digital twin model depends entirely on high-quality, up-to-date data. Currently, spatial, utility, and environmental datasets in Serbia are fragmented across various public enterprises, municipal secretariats, and directorates. Overcoming this socio-technical barrier requires the establishment of strict, open data-sharing protocols and clear institutional accountability for maintaining cross-sectoral data integrity [20].
- **Privacy and the Ethical Boundary of Urban Surveillance:** To optimize traffic flow and environmental metrics, smart city frameworks require a continuous spatio-temporal data stream, which naturally raises legitimate public concerns regarding citizen surveillance. The ethical boundary is crossed when a municipality collects

excessive personal data, uses it for unannounced tracking, or fails to define transparent retention limits. To align with the European Union's *AI Act* and local data protection regulations, cities must enforce anonymized edge computing. For instance, AI-driven traffic cameras do not need to capture license plates or facial biometrics; they only require vehicle counts, velocities, and queue lengths processed locally at the intersection level, thereby safeguarding citizen privacy [21].

- **Algorithmic Bias and the Preservation of Urban Identity:** AI algorithms are not inherently neutral tools; they optimize exclusively for the specific parameters and mathematical goals defined by their programmers. If an algorithm is tasked solely with maximizing real estate floor-area ratios or traffic throughput, it will inevitably generate a mathematically perfect yet unlivable space. AI completely lacks empathy, historical context, and an understanding of cultural heritage—elements that comprise the historical and cultural identity of an inherited urban fabric. Therefore, AI must strictly serve as an expert analytical assistant, while final evaluation, value-based synthesis, and holistic decisions remain the sole responsibility of human urban planners [22].

6. CONCLUSION

The integration of Artificial Intelligence and Nature-based Solutions represents a paradigm shift toward data-driven, climate-resilient urban planning. Global examples confirm that technology is most effective when deployed to address tangible urban and environmental challenges rather than serving as a political showcase. For the city of Niš, utilizing exploratory scientific modeling and pilot testing targeted AI concepts—such as predictive green infrastructure placement and dynamic traffic management—offers a realistic pathway toward mitigating severe microclimatic and air pollution challenges. A phased implementation based on pilot projects and interdisciplinary institutional cooperation represents the most feasible approach for introducing AI-supported ecological planning under current local conditions.

The proposed framework is intended to support evidence-based decision-making by integrating environmental data, spatial analysis, and AI-assisted planning simulations into the planning process. Although its practical implementation will depend on the gradual development of local digital infrastructure and institutional capacities, the framework provides a realistic foundation for future research, pilot applications, and interdisciplinary collaboration in climate-resilient urban planning.

Ultimately, the success of a smart city is not measured by its digital sophistication, but by the clean air, green spaces, and sustainable living environment it secures for its citizens. Accordingly, the future of smart cities should be understood less as a technological project than as an ecological and human-centered planning paradigm, in which digital intelligence supports—rather than replaces—the professional judgment of urban planners.



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