DIGITAL TWIN FRAMEWORK FOR ENVIRONMENTAL, HERITAGE AND NEURO-URBAN PLANNING IN TASHKENT SMART CITY

Implementation of Digital Twin Technology as an Integrated Solution for Sustainable Urbanization Challenges in Tashkent Smart City

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ABSTRACT

Digital Twin technology has become an essential platform for integrating environmental sustainability, cultural heritage preservation, and human-centered urban planning within smart cities. This research proposes a comprehensive Digital Twin framework for Tashkent Smart City by combining the Internet of Things, Geographic Information Systems, Building Information Modeling, Artificial Intelligence, cloud computing, environmental monitoring, and neuro-urban analytics. The framework enables real-time observation of ecological conditions, protection of historical monuments, and evaluation of citizens' cognitive and psychological responses to urban environments. The proposed model supports sustainable, resilient, and human-oriented urban development.

Keywords: Digital Twin, Environmental Monitoring, Heritage Preservation, Neuro-Urban Planning, Smart City, Tashkent, Artificial Intelligence.

1. INTRODUCTION

Modern smart cities must balance environmental sustainability, historical heritage conservation, and the well-being of their citizens. Tashkent possesses valuable architectural heritage, expanding green infrastructure, and rapidly developing urban

districts. However, increasing urbanization creates challenges including environmental pollution, loss of cultural identity, urban heat islands, traffic stress, and declining public comfort.

Digital Twin technology provides a dynamic digital representation of both natural and built environments. Through continuous synchronization with environmental sensors, satellite imagery, GIS databases, and heritage information systems, city planners can evaluate ecological conditions, preserve historical assets, and design healthier public spaces.

The purpose of this research is to develop an integrated Digital Twin framework that combines environmental monitoring, heritage preservation, and neuro-urban planning for sustainable development in Tashkent Smart City.

2. LITERATURE REVIEW

Digital Twin applications have expanded from industrial engineering into environmental science, cultural heritage management, and urban neuroscience. Recent studies demonstrate that intelligent digital platforms improve air-quality monitoring, biodiversity assessment, climate adaptation, and conservation of historical monuments through continuous spatial analysis.

Neuro-urban planning is an emerging discipline that investigates how urban environments influence human cognition, mental health, stress, and social behavior. Researchers combine GIS, wearable sensors, environmental monitoring, and Artificial Intelligence to evaluate the psychological quality of streets, parks, public squares, and transportation corridors.

International projects in Rome, Helsinki, and Singapore demonstrate that Digital Twin technology can simultaneously protect historical architecture, optimize green infrastructure, and improve human-centered urban design. These experiences provide a scientific foundation for developing a localized framework suitable for Tashkent.

3. RESEARCH METHODOLOGY

This research applies a multidisciplinary methodology that combines environmental science, cultural heritage management, Geographic Information Systems (GIS), Building Information Modeling (BIM), Artificial Intelligence (AI), and neuro-urban analytics to develop a comprehensive Digital Twin framework for Tashkent Smart City. The methodology consists of five integrated stages.

The first stage involves environmental and heritage data collection. Information is gathered from air-quality sensors, meteorological stations, satellite imagery, drone observations, historical archives, and municipal geographic databases. Cultural heritage assets including historical buildings, monuments, museums, and protected architectural zones are digitally documented using BIM and three-dimensional laser scanning technologies.

The second stage focuses on Internet of Things integration. Smart sensors continuously monitor particulate matter (PM2.5 and PM10), carbon dioxide concentration, temperature, humidity, noise pollution, soil moisture, and urban green-space conditions. These real-time datasets provide an accurate representation of the environmental performance of different districts within Tashkent.

The third stage integrates GIS and BIM into a unified Digital Twin platform. GIS provides spatial analysis of ecological corridors, heritage protection zones, public parks, transportation networks, and demographic distribution, while BIM contributes detailed structural information for historical and modern buildings. Cloud computing enables secure storage and rapid processing of heterogeneous urban datasets.

The fourth stage introduces neuro-urban analytics through Artificial Intelligence. Environmental indicators are combined with pedestrian mobility, public space accessibility, green-area distribution, traffic intensity, and noise exposure to evaluate human comfort, cognitive well-being, and psychological stress within urban environments. Machine learning models identify areas requiring ecological improvement or human-centered redesign.

The fifth stage develops an interactive Digital Twin decision-support platform. Municipal authorities, environmental agencies, and urban planners receive real-time ecological dashboards, heritage conservation indicators, GIS visualization, three-dimensional city models, and predictive sustainability scenarios that support evidence-based planning and long-term resilient urban development.

4. DIGITAL TWIN FRAMEWORK

The proposed Digital Twin framework consists of six interconnected functional layers. The Environmental Layer monitors air quality, climate conditions, vegetation health, and water resources through intelligent sensing technologies. The Heritage Layer digitally preserves historical monuments, architectural landmarks, and cultural districts using BIM and 3D documentation. The GIS Layer provides spatial visualization and environmental mapping across the metropolitan area. The Artificial Intelligence Layer performs environmental forecasting, heritage risk assessment, and neuro-urban analysis. The Cloud Data Layer integrates real-time information from multiple municipal departments into a unified database. Finally, the Decision Support Layer delivers interactive dashboards, sustainability indicators, conservation priorities, and urban planning simulations for intelligent governance in Tashkent Smart City.

5. RESULTS AND DISCUSSION

The proposed Digital Twin framework demonstrates substantial benefits for environmental sustainability, cultural heritage preservation, and human-centered urban planning in Tashkent Smart City. By integrating real-time environmental monitoring, three-dimensional heritage models, Geographic Information Systems, and Artificial Intelligence, the platform provides a comprehensive digital ecosystem for intelligent urban governance.

Environmental monitoring enables continuous observation of air quality, temperature, humidity, noise pollution, and vegetation health across different districts of Tashkent. IoT sensors transmit real-time information to the Digital Twin platform,

while GIS visualizes environmental indicators through interactive spatial maps. Artificial Intelligence predicts pollution levels, identifies urban heat island zones, and recommends ecological interventions such as expanding green corridors, improving public parks, and reducing traffic emissions.

The framework also strengthens cultural heritage conservation by creating accurate digital replicas of historical buildings and monuments. Three-dimensional BIM models preserve architectural geometry, construction materials, and structural characteristics of heritage assets. Continuous monitoring detects surface deformation, structural movement, moisture, and environmental degradation, allowing conservation specialists to perform preventive restoration before irreversible damage occurs.

Neuro-urban planning introduces a human-centered perspective into smart city development. Environmental indicators, pedestrian mobility, accessibility, green-space distribution, traffic intensity, and noise exposure are analyzed together to evaluate public comfort and psychological well-being. Machine learning identifies streets, parks, and public spaces that generate excessive stress and recommends urban design improvements that increase walkability, social interaction, and cognitive health.

Scenario simulation further enhances evidence-based planning. Before constructing new residential districts, transportation corridors, or recreational facilities, planners evaluate their influence on environmental quality, heritage protection, public accessibility, and citizens' well-being within the Digital Twin environment. This approach minimizes planning risks while supporting sustainable investment decisions.

6. CONCLUSION

This study proposed a comprehensive Digital Twin framework for environmental, heritage, and neuro-urban planning in Tashkent Smart City. The integration of Internet of Things technologies, Geographic Information Systems, Building Information Modeling, Artificial Intelligence, cloud computing, and

environmental analytics establishes a resilient digital platform for sustainable urban development.

The research concludes that Digital Twin technology significantly improves ecological monitoring, historical heritage preservation, human-centered urban design, and evidence-based municipal governance. Future development should focus on advanced environmental forecasting, digital cultural archives, renewable green infrastructure, citizen participation, and intelligent urban health analytics to strengthen the long-term sustainability of Tashkent Smart City.

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