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Smart Technologies for Climate-Resilient Urban Road Infrastructure: A Systematic Review

Maryam Khazaee[1]*, Luca Bertolini[1], Fabrizio D'Amico[1] and Alessandro Calvi[1]

[1] Department of Civil, Computer Science, and Aeronautical Technologies Engineering, Roma Tre University, Rome, Italy

*E-mail: maryam.khazaee@uniroma3.it

Abstract. Urban road infrastructure is increasingly vulnerable to climate change impacts such as extreme weather, flooding, and heat stress, threatening its safety, functionality, and longevity. This systematic review investigates how smart technologies, such as Building Information Modeling (BIM), Geographic Information Systems (GIS), Digital Twin (DT), Internet of Things (IoT), Artificial Intelligence (AI), Big Data, and Remote Sensing (RS), can enhance the climate resilience of urban road networks. The review paper demonstrates that each technology offers complementary features like life-cycle planning, predictive analytics, and real-time monitoring. GIS supports spatial analysis; BIM enables infrastructure modeling; BIM-GIS integration enhances interoperability; Remote Sensing and IoT provide environmental data; Digital Twins offer simulation and monitoring; and AI and Big Data enable predictive maintenance, risk modeling, and decision-making. The review proposes a layered framework integrating these technologies and highlights challenges like data interoperability and policy alignment for effective implementation. The paper offers valuable insights to inform adaptive and sustainable strategies for developing climate-resilient urban roads.

Keywords: Climate-resilient infrastructure, Urban Roads, Smart Technologies, Building Information Modeling (BIM), Geographic Information Systems (GIS), Digital Twin (DT), Remote Sensing (RS).

1. Introduction

Climate change has made urban road infrastructure increasingly vulnerable to harsh weather, flooding, heat stress, and structural degradation. These issues compromise infrastructure, urban safety and liveability, highlighting the urgent need for adaptive measures [1]. Integrating climate change considerations into transportation infrastructure planning is crucial for long-term sustainability and minimizing economic and societal risks from climate-induced disruptions [2]. Globally, governments and policymakers have recognized the need for robust climate resilience strategies to mitigate these escalating risks. Climate resilience refers to the capacity of social, economic, and environmental systems to withstand hazardous events while maintaining their core functions and structures [3].In this context, smart technologies emerge as a critical enabler of climate resilience, particularly within urban road infrastructure. These technologies offer innovative solutions to monitor, adapt to, and even anticipate the impacts of climate change. They encompass a range of digital and communication technologies that facilitate efficient, responsive, and sustainable urban systems. The concept of smart technologies generally aligns with a broader understanding of smart cities, which utilize digital technologies and data analytics to enhance service delivery, improve urban quality of life, and promote sustainability [4].

Several review papers have analyzed climate change's influence on road networks and recommended adaptation strategies. For instance, Abreu et al.[2] systematically reviewed the analysis of climate-related mitigation methods and identified weaknesses in long-term resilience planning. Argyroudis et al.[5] emphasized that emerging digital technologies and predictive analytics play a crucial role in improving critical infrastructure resilience. Similarly, Rezvani et al. [6] explored the effectiveness of GIS-based decision support tools in improving urban resilience.

Smart technologies have become key enablers of infrastructure resilience. Numerous researchers have explored the role of Building Information Modeling (BIM) and Geographic Information Systems (GIS) in infrastructure resilience. Bradley et al.[7], Cepa et al.[8] and Castaneda et al.[9] investigated BIM implementation in infrastructure projects and identified key issues such as data integration and project governance, while also noting the benefits of automation and digitalization. Song et al.[10] explored the potential of BIM-GIS convergence in infrastructure planning, and Cepa et al.[11] proposed a hybrid approach for road asset management using digital twin applications.

Despite the growing application of smart technologies for climate resilience on urban road infrastructure, significant gaps remain in understanding how to effectively integrate a wide range of smart technologies into unified decision-making frameworks for climate-resilient urban roads to ensure sustainability and long-term adaptation. Most existing studies focus on individual technologies in isolation, such as BIM, GIS, and Artificial Intelligence (AI), without offering a comprehensive assessment of their potential or interaction. This review paper aims to bridge the identified gaps by systematically analysing the role of emerging smart technologies, such as BIM, GIS, Internet of Things (IoT), Digital Twin (DT), Remote Sensing (RS) and AI, in enhancing the climate resilience of urban road infrastructure. Furthermore, it outlines how these technologies can interact synergistically within an integrated framework to strengthen infrastructure against climate-related risks.

2. Research Methodology

Systematic reviews require the implementation of a predefined and clear search strategy. As a foundation, the research questions were first articulated to guide the scope and focus of the review. This study aims to address the following research question:
RQ: What is the role of BIM, GIS, IoT, digital twins, and AI in improving the resilience of urban road infrastructure to climate-related challenges?

The research methodology, structured in alignment with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, ensures a transparent and replicable process. PRISMA provides a standardized approach to systematically identifying, screening, selecting, and including literature in systematic reviews. As outlined in Figure 1, the methodology consists of four sequential phases: (1) data search and selection, (2) data extraction, (3) synthesis and results, and (4) framework Application, designed to systematically identify and analyze literature on how smart technologies enhance climate resilience in urban road infrastructure.

A structured search using the SCOPUS database targeted key terms related to BIM, GIS, transportation and climate resilience to ensure comprehensive literature coverage. The filtration process involved multiple stages: initial filtering based on language, publication type, subject area, publication stage, and open access status; followed by temporal restrictions on publication years;

and concluding with a two-step manual screening of titles, keywords, and abstracts based on thematic relevance. The following phases used qualitative methods, including bibliometric analysis with VOSviewer and content analysis via NVivo, to examine publication trends and identify key technologies. Insights from these analyses were then integrated into a conceptual framework demonstrating how technologies like BIM, GIS, IoT, Digital Twins, and AI can strengthen climate resilience in urban road systems.

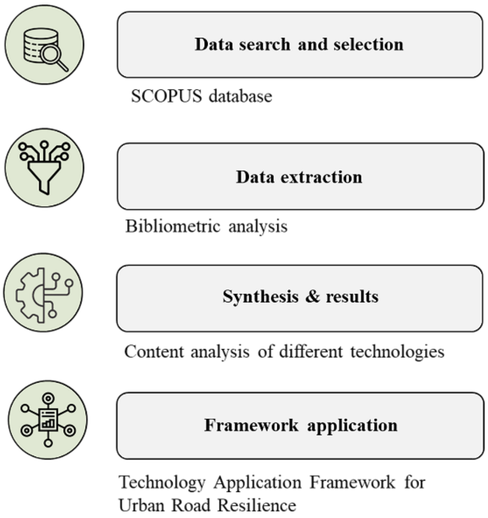

Figure 1. Flowchart of the methodology structure for the systematic review.

3. Results & Analysis

3.1. Geographic Information Systems applications

Geographic Information Systems (GIS) play a crucial role in enhancing the climate resilience of urban road infrastructure by offering geospatial analysis, hazard mapping, and environmental monitoring. GIS complements DT technology by supporting flood risk assessment, infrastructure planning, and disaster response through spatial intelligence. Studies highlight various GIS applications: Ahmad et al.[12] developed a Storm Water Management Model (GIS-SWMM) framework in Lahore for flood-prone area identification and improved stormwater systems using low-impact development (LID) practices. Chamorro et al.[13] introduced SIGeR-RV (Sistema Integrado de Gestión del Riesgo–Redes Viales) in Chile, integrating hazard maps and vulnerability data for multi-hazard road network management. In Southeast Texas, GIS-based modeling with NASA's sea-level rise data simulated flooding scenarios to guide adaptive road infrastructure planning [14].

Additionally, GIS has proven effective for environmental monitoring and transportation resilience. Li et al.[15] applied GIS to analyze environmental factors like air pollution and urban heat islands for adaptation strategies, while Czyża & Kowalczyk[16] used GIS to assess emissions and thermal stress on roads. In Poland, GIS and RS were used to optimize blue-green infrastructure placement to enhance urban liveability and resilience [17]. Kaya et al.[18] used GIS to assess tornado risk and model road disruptions in Texas and Mexico, highlighting GIS's potential for disaster policy and emergency response planning. Rezvani et al.[6] reinforced GIS's value as a decision-support tool in urban resilience, urging the adoption of standardized frameworks and AI-enhanced simulations for comprehensive risk assessment.

3.2. Building Information Modeling applications

Building Information Modeling (BIM) enhances climate resilience in urban road infrastructure by complementing DT and GIS technologies through integrated data visualization, 3D modeling, and lifecycle assessment. While GIS provides spatial intelligence and DT offers real-time monitoring and predictive analytics, BIM supports sustainable infrastructure design, efficient building operations, and long-term environmental performance. BIM is particularly impactful in smart infrastructure and public projects, as seen in the EU's BIM adoption policy and Spain's Ministry of Development initiatives [19]. When integrated with AI and smart city systems, BIM fosters cross-disciplinary collaboration and sustainable decision-making, despite existing challenges like regulatory compliance, decentralized workflows, and interoperability [19], [20].

BIM's integration with Life Cycle Assessment (LCA) and GIS enables robust assessment of greenhouse gas emissions during both operational and embodied life stages of construction. Its ability to generate 3D models also supports hazard simulations, such as hurricane pressure forecasting via Computational Fluid Dynamics (CFD) [21]. Studies by Jrade et al.[22] and Gilbert et al.[23] showed how combining BIM with Bridge Information Modeling (BrIM), Life Cycle Cost (LCC) and geospatial utilities enhances resilience, sustainability and planning efficiency in road and bridge infrastructure. Furthermore, Kaewunruen et al.[24] highlighted BIM's role in railway bridge maintenance and climate adaptation, demonstrating reductions in project costs and emissions while improving infrastructure resilience and lifecycle management.

3.3. BIM-GIS integrations

The integration of BIM and GIS has become increasingly valuable in enhancing the climate resilience of urban infrastructure. While GIS contributes spatial intelligence for infrastructure planning and territorial analysis, BIM delivers detailed 3D modeling and supports efficient project management and sustainability. Even though differences in data formats and scales, the use of open standards such as CityGML (City Geography Markup Language) and IFC (Industry Foundation Classes), and tools like ArcGIS and InfraWorks (Autodesk®), has improved interoperability between these technologies [25]. This integration enables emissions reduction, optimized resource management, disaster awareness, and predictive maintenance through technologies like AI and Machine Learning (ML) [26]. This integration has optimized waste management and reduced construction emissions. The Life Cycle Assessments (LCAs) showed significant reductions in greenhouse gas emissions across various project stages [20]. In other infrastructure, such as bridges, combining BIM's modeling capabilities with GIS's geospatial analytics supports adaptive design and also real-time Non-Destructive Testing (NDT) enhances structural resilience [27].

Beyond sustainability, BIM-GIS integration significantly advances disaster resilience and climate risk analysis. It supports wind hazard modeling and CFD simulations, allowing infrastructure to adapt to extreme weather conditions [21] and enables automated design updates in real-time based on environmental changes. This dynamic integration is essential in post-disaster scenarios for damage assessment and resource planning [11]. The framework of BIM-GIS-Digital City Entities (DCEs) aids in system-level flood vulnerability assessments, benefiting interconnected systems like roads and drainage [28]. Moreover, hybrid models enhance urban planning by merging micro-level design details with macro-environmental insights [11]. Another application of this integration is predictive maintenance that can be improved through automated design revisions from geospatial inputs [19]. However, several challenges, like data compatibility and limited interoperability, remain, and there is a need for standardized integration frameworks to realize the potential of BIM-GIS synergies completely.

3.4. Remote Sensing and IoT applications

Remote Sensing (RS) enhances the climate resilience of urban road infrastructure through environmental monitoring, disaster risk assessment, and predictive maintenance. RS, along with DT, BIM, and GIS, provides high-resolution geospatial data for flood hazard analysis, road condition monitoring, and infrastructure planning. For instance, in Southeast Texas, LiDAR-based Digital Elevation Models (DEMs) and sea-level rise projections were used to simulate future inundation scenarios [14], while studies using HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System) and HEC-RAS (Hydrologic Engineering Center – River Analysis System) hydrologic models evaluated landslide and flood risks by using satellite imagery and precipitation-runoff data [6]. RS platforms such as MODIS, ASTER, Landsat, and SAR have proven effective in mapping flood zones and detecting hazards in challenging conditions like cloud cover [29]. In the Ganges River Delta, Landsat and deep learning were employed for real-time flood monitoring [30]. Similar methods supported wildfire risk modeling and bridge vulnerability assessment [31]. UAV-LiDAR and digital photogrammetry also aid urban ecological planning, Blue-Green Infrastructure placement [17] and structural integrity evaluation [32] [33] [27].

IoT significantly complements RS by enabling real-time environmental monitoring and infrastructure adaptation. IoT-integrated GIS and RS systems monitor environmental changes to update adaptive strategies, especially in land-constrained and coastal regions. Sensor networks enhance sea-level rise modeling and flood risk assessment [14],[15]. IoT integration with BIM supports data-driven decision-making for sustainable urban development and hydropower infrastructure [15]. Furthermore, combining IoT with RS tools, like MODIS and LiDAR, advances disaster risk mapping, flood forecasting, and source planning [34]. Cross-border data-sharing initiatives using IoT and UAV-LiDAR technologies foster collaboration for disaster resilience and proactive infrastructure management [31], [33].

3.5. Digital Twin applications

Digital Twin (DT) technology is increasingly being applied to enhance climate resilience in urban road infrastructure through real-time data integration, simulations, and predictive analytics. Key applications include disaster resilience and hazard management, flood control, structural health monitoring, emergency response, and underground utility mapping. Vishnu et al.[35] highlighted DT's role in catastrophe risk assessment using statistical methods, deep learning, and Convolutional Neural Networks (CNNs), enabling hazard simulation and geographic analysis. In Cosenza, Italy, a decentralized real-time control system was implemented by combining AI with hydrodynamic models to mitigate flooding [36]. Web-GIS integrated with DT frameworks has supported real-time disaster evaluation and seismic risk monitoring [31]. For structural health, the Polyfytos Bridge project employed Unmanned Aerial Vehicles (UAV) imagery and Persistent Scatterer Interferometry (PSI) for continuous monitoring [5], while the Minnamurra Railway Bridge used DTs for climate impact assessments and maintenance prediction [24]. In emergency response, DTs helped optimize evacuation after the Fukushima disaster, using Unmanned Aerial Vehicles (UAVs) and large-scale simulations [37]. DTs also aid infrastructure planning, as seen in the UK's initiatives (National Underground Asset Register (NUAR) and Centre for Digital Built Britain (CDBB)), by mapping underground utilities to avoid excavation damage and improve road sustainability [23].

3.6. Artificial Intelligence and Big Data applications

Artificial Intelligence (AI) and Big Data are greatly improving the resilience of urban road infrastructure through enabling real-time monitoring, predictive analysis and autonomous decision-making. AI enhances the data processing for data from DT models, GIS-based spatial analysis and BIM-driven infrastructure management. Big Data combines diverse environmental datasets to support comprehensive risk assessments. These technologies improve and enhance infrastructure planning, maintenance and disaster response and make sure that urban road networks are more resilient to climate change and environmental challenges. AI and Machine Learning (ML) techniques accelerate predictive analysis, risk evaluation, and real-time monitoring. When combined with GIS, BIM and DT technologies, they improve data quality and automate spatial development monitoring [26]. AI can support road resilience through leveraging tools such as computer vision for urban classification, predictive modeling for water and transport system failures and real-time hazard mapping using satellite data like Sentinel-3(European Space Agency (ESA) satellite mission, part of the Copernicus programme) [6]. Additionally, AI supports infrastructure management by providing real-time updates via open-source data, RS and automated land-use detection [17]. ML models like Boosted Regression Trees (BRT) and Generalized Linear Models (GLM) are effective in enhancing flood risk assessment [6]. Furthermore, other ML models, Random Forest (RF) and Support Vector Machines (SVM), have been shown to improve flood prediction accuracy [30], and AI-driven UAV inspections help mitigate risks related to transmission line failures and wildfires [38]. Even though these developments exist, challenges remain, such as data privacy concerns, interoperability issues, and regulatory frameworks, which continue to hinder the full integration of these technologies [5].

Big Data is fundamental for enhancing urban road infrastructure resilience by enabling real-time data collection, predictive analytics, and evidence-based decision-making. Big Data, when combined with GIS, RS, AI, IoT and cloud computing, strengthens disaster management, risk assessment, and infrastructure adaptation. It complements DT and BIM technologies [19]. Several research studies have demonstrated Big Data's application in flood risk assessment, stormwater management, and climate adaptation in urban areas. For example, multi-source data fusion, involving Synthetic Aperture Radar (SAR) imagery and data fusion techniques, has been used to detect inundated areas in flood risk assessments, as observed during Pakistan’s 2022 mega-flood [39]. Furthermore, Google Earth Engine supports real-time flood monitoring and improves climate preparation through hydrological and meteorological models [29]. Beyond disaster resilience, Big Data-driven GIS and simulation frameworks optimize stormwater management in sponge cities, urban drainage systems and flood-prone areas such as airports [36]. Big Data and GIS support urban climate adaptation techniques like wind corridor planning to mitigate urban heat island effects and enhance air quality [40]. Additionally, a geospatial framework can evaluate the resilience of urban infrastructure by assessing access flexibility, disruption risk, and vulnerability [41]. However, processing large geospatial datasets efficiently remains a challenge and requires continued advancements in AI and deep learning to improve disaster resilience and climate adaptation strategies [42].

4. Discussion & Conclusion

Each of the mentioned technologies offers unique contributions to enhancing climate resilience. DT technology presents real-time infrastructure monitoring and predictive simulations for disaster management and flood control. GIS supports crucial spatial analysis for hazard mapping, environmental monitoring, and urban planning. BIM promotes sustainable design by applying detailed 3D modeling and life-cycle assessments. Furthermore, RS provides high-resolution geographic data for assessing threats like floods and sea-level rise, as IoT collects continuous environmental data to assist adaptive solutions. Ultimately, AI and Big Data offer enhanced analytics enabling predictive maintenance and data-driven decision-making. All technologies promote adaptive, efficient and resilient road infrastructure planning and management.

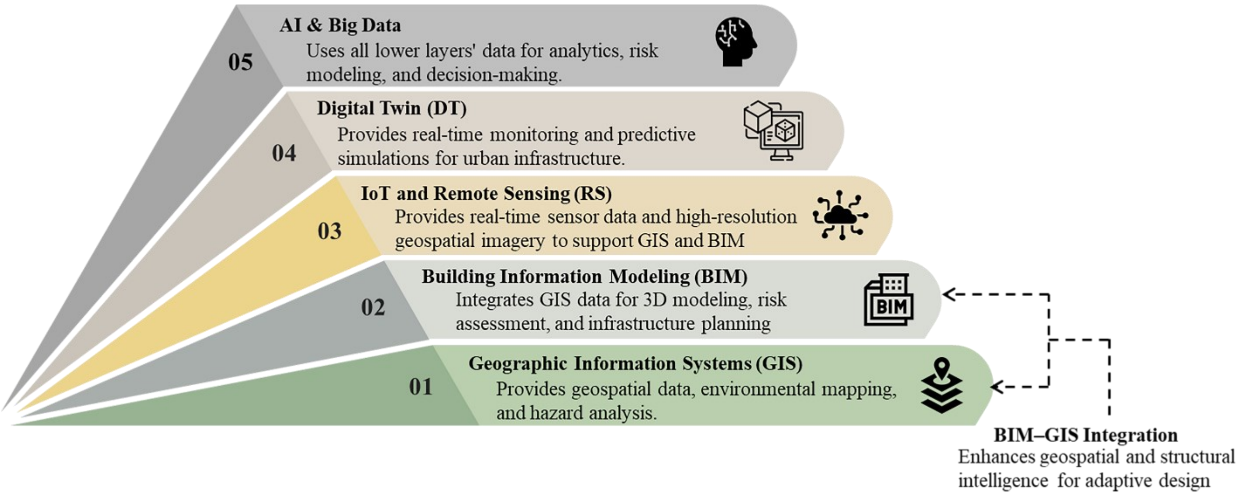

Figure 2. Layered GIS-BIM-IoT-RS-DT-AI Framework for Urban Road Resilience.

The integration of GIS, RS, BIM, DT, AI, and Big Data in urban road resilience is critical for enhancing climate adaptation and disaster readiness. Figure 2 illustrates a multi-layered GIS-BIM-IoT-RS-DT-AI structure, depicting the hierarchical interplay of these technologies. GIS is the foundation layer by providing geospatial data needed for hazard mapping, land-use planning, and environmental monitoring. At the next layer, BIM utilizes GIS-based geospatial data to build accurate 3D models and create digital infrastructure plans and structural analysis. Furthermore, BIM-GIS integration bridges the gap between spatial analysis and physical infrastructure modeling, facilitating interoperability and enabling comprehensive assessment of both geographic context and design detail. In the third layer, RS and IoT provide dynamic data input. RS offers large-scale environmental data through satellite imagery and aerial surveys on the urban environment, which enables the identification of vulnerable areas such as flood-prone zones and deteriorating infrastructure. IoT sensors deliver real-time data and in-situ measurements of physical assets. This layer enriches models with both historical and live data that is essential for accurate monitoring and forecasting. The DT layer leverages all preceding inputs to create a synchronized and real-time virtual representation of infrastructure systems. DT also enables continuous monitoring and predictive simulation for adaptive management of urban infrastructure. At the top level, AI and Big Data analytics complement decision-making with organized datasets, like GIS and RS data for automated risk modeling, predictive analysis, and disaster response optimization.

Future research should prioritize the development of standardized integration protocols to address interoperability challenges among BIM, GIS, IoT, Digital Twins (DT), and RS. Establishing common data exchange formats, ontologies, and cross-platform frameworks is essential for effective smart infrastructure management. Enhancing AI-driven simulations through improved calibration, validation, and reinforcement learning can support more accurate forecasting of climate-induced impacts and maintenance needs. Expanding the use of high-resolution GIS and RS data with predictive climate models will also strengthen adaptation planning. Furthermore, Empirical validation through pilot projects in diverse urban settings is crucial to assess the real-world feasibility and scalability of smart technologies. Policy frameworks should promote cross-sector collaboration, open data exchange, and handle cybersecurity and privacy issues. Inclusive implementation of these technologies requires socio-technical activities such as capacity-building and public involvement.

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