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The prospects and perils of smart urban development: A review of artificial intelligence implementation in sustainable city projects

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Abstract

Urban areas now constitute the primary habitat for most of the global population, a demographic shift that has exacerbated longstanding urban challenges. In response, cities are increasingly turning to emerging information and communication technologies and artificial intelligence (AI) as potential solutions. This study provides a critical review of the predominant urban issues and examines their interconnection with contemporary smart city initiatives worldwide. Through an analysis of international case studies from Singapore, Spain, the Netherlands, and Copenhagen, this research aims to derive valuable insights and lessons to inform the development of scenarios for future sustainable urban models. The study highlights that while AI and smart technologies hold significant promise for advancing urban sustainability, their implementation faces considerable challenges. These include critical social implications, such as the erosion of privacy, alongside economic constraints and heterogeneous regulatory landscapes across national contexts. Furthermore, the analysis identifies Dutch smart urbanism initiatives as particularly noteworthy. Among the cases examined, the Dutch approach is distinguished by its pronounced emphasis on mitigating social issues and fostering public participation in the co-creation of future urban frameworks.

Keywords: Smart cities; Artificial intelligence; Mobility; Waste management; Energy management; Virtual Singapore; Internet of Things; City-Zen project

1. Introduction

Cities have emerged as the primary organizational form for human settlement over the past three decades (Egger, 2006). The world's population reached 7 billion in

2011 (Hassan & Lee, 2015a), with more than half of the population residing in urban areas (UN-Habitat, 2003), although liveable urban land covers <3 percent of the planet's surface. Projections indicate that by 2030, approximately 60 percent of the global population will live in cities (Egger, 2006).

While the 20th century is often characterized as the age of urbanization, the 21st century has further amplified this trajectory (Lehmann, 2010). UN-Habitat (2022) and the UN-Habitat (2003) estimate that nearly 80 percent of future urban growth will occur in developing countries, with Asia and Africa experiencing the most rapid expansion. As cities transform into "megacities" of 10 million and "meta-" or "hyper-cities" of 20 million people (UN-Habitat, 2003), the adoption of smart technologies and artificial intelligence (AI)-driven tools offers a promising avenue for addressing these intensifying urban challenges (Hassan & Awad, 2018).

A human-centric approach is fundamental to ensuring that technological innovations empower rather than marginalize urban residents (Alshammari *et al.*, 2022; Sadowski, 2020). This requires designing smart grids, platforms, and public interfaces that prioritize accessibility and cultural relevance, thereby reducing digital inequality (Alverti *et al.*, 2018).

AI operationalizes this principle by enabling adaptive interventions, such as optimizing public transport to serve underserved districts (Khamis, 2021) and auditing algorithms to identify and correct discriminatory service allocations (Green, 2019). Embedding equity is both an ethical requirement and a cornerstone of long-term urban resilience, ensuring that the benefits of sustainability and digitalization are broadly shared (Fainstein, 2010; Yigitcanlar *et al.*, 2020).

Sustainability and resilience are mutually reinforcing pillars of future-proof cities (Hassan & Lee, 2015b). Sustainability focuses on reducing ecological burdens through efficient resource use (UN-Habitat, 2022), while resilience emphasizes the capacity to absorb and adapt to shocks such as extreme weather (Meerow *et al.*, 2016). Green infrastructure reduces vulnerability, and resilient governance protects sustainability achievements (Sharifi & Yamagata, 2018). AI supports both goals by optimizing energy flows in smart grids (Zanella *et al.*, 2014), improving efficiency across water and waste systems (Fang *et al.*, 2023), and modeling climate risks to inform adaptive strategies (Bibri & Krogstie, 2017).

Central to this transformation is the emergence of data-driven decision-making (DDDM), which replaces reactive planning with continuous, evidence-based evaluation. Drawing on the Internet of Things (IoT) sensors, satellite imagery, and participatory data sources, DDDM enables the real-time monitoring of urban systems (Kitchin, 2014). AI and machine learning reveal hidden patterns, simulate policy scenarios, and refine resource allocation (Bibri & Krogstie, 2017). Digital twins—virtual city replicas—allow planners to test the impacts of infrastructure decisions or climate events before implementation, thereby reducing risk and improving service delivery (Batty, 2018).

A critical enabler of DDDM is overcoming the chronic siloing of urban infrastructure. AI promotes integration and interoperability by creating unified data architectures that connect transport, energy, water, and waste systems (Allam & Dhunny, 2019; Bibri *et al.*, 2023). Integrated analytics yield holistic insights—for example, by synchronizing traffic systems to reduce emissions while coordinating energy loads in the smart grid (Mohanty, 2025). This integration supports synergistic solutions, such as waste-to-energy conversion, enhancing overall urban metabolism (Yigitcanlar *et al.*, 2020).

This integrated data environment also advances the use of predictive and prescriptive analytics. Machine learning models forecast critical scenarios, such as congestion patterns or flood risks (Jain & Pandey, 2025), while prescriptive analytics generates recommended interventions, including dynamic transport scheduling or energy load adjustments to avoid grid stress (Bibri & Krogstie, 2020). In this context, digital twins function as analytical sandboxes for evaluating policy options and optimizing outcomes (White *et al.*, 2021).

In the following section, this study outlines the fundamental principles identified through the review process, including the criteria for selecting the primary urban domains and the rationale for choosing the case studies. It ends with a discussion of limitations arising from the exclusion of other potential examples.

2. Methodology and limitations

This study employed a narrative approach to examine the relationship between AI, smart technologies, and sustainable urban development, focusing on five key urban domains: urban planning and design, mobility, waste management, energy systems, and water management. These domains constitute the principal arenas through which AI and smart technologies can advance sustainable urban development.

These domains are inherently data-rich, systemically interconnected, and governed by quantifiable performance indicators, enabling intelligent systems to monitor, predict, and optimize urban processes in real time. Together, they form the core infrastructural subsystems of sustainable cities, shaping environmental performance, resource efficiency, and overall urban quality of life. By examining these interlinked areas, the study demonstrates how data-driven innovation can enhance urban resilience and sustainability through a case-study-based review.

The analysis was conducted on four internationally recognized models: Virtual Singapore, Barcelona's integrated IoT system, Amsterdam's City-Zen project, and Copenhagen's AI-driven hydrological management. These cases were selected according to five criteria: (i) Representativeness and global recognition; (ii) diversity of contexts and governance models; (iii) empirical reliability; (iv) maturity and demonstrated impact; and (v) conceptual and analytical coherence. These criteria inform the framework and highlight the limitations presented in Figure 1.

2.1. Representativeness and global recognition

Each case represents a leading global benchmark in its respective AI application domain. Virtual Singapore exemplifies AI-enabled digital twin governance for spatial simulation and planning. Barcelona is a widely cited model for AI-supported IoT integration and real-time urban management. Amsterdam's City-Zen project demonstrates AI's role in urban energy transition through renewable integration and predictive load management. Copenhagen represents a global exemplar of AI in environmental resilience, particularly in climate-responsive and hydrological systems. Collectively, these cases illustrate distinct functional dimensions of AI in governance, infrastructure, energy, and environmental management while jointly covering the environmental, economic, and social pillars of sustainability.

2.2. Diversity of contexts and governance models

The selected cities also encompass diverse regional and institutional contexts. Singapore reflects a state-driven digital governance model with strong institutional coordination. Barcelona represents a municipal innovation approach grounded in citizen-centric and participatory principles. Amsterdam exemplifies collaborative energy governance involving public authorities, private actors, and civic partners. Copenhagen demonstrates climate-oriented governance where AI is embedded within environmental and public policy integration. This diversity enables comparative analysis across contrasting political, socioeconomic, and cultural conditions.

2.3. Availability and reliability of empirical data

These cases were selected due to the availability of robust empirical evidence derived from peer-reviewed studies and official policy reports. Projects such as Virtual Singapore and City-Zen have been extensively documented in academic literature (e.g., urban studies, cities, energy informatics), while Barcelona's IoT programs and Copenhagen's climate resilience systems benefit from open municipal datasets and international benchmarks. This ensures that the comparative analysis rests on verifiable, scientifically credible data.

2.4. Maturity and demonstrated impact

All selected examples have progressed beyond pilot phases and produced measurable sustainability outcomes. These

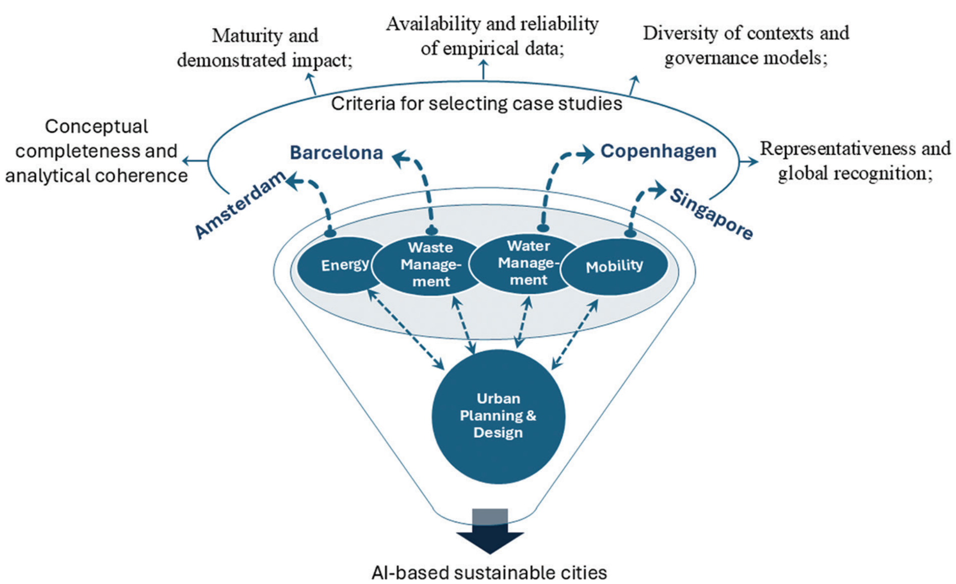

Figure 1. Conceptual framework illustrating the role of artificial intelligence (AI) across urban domains, including examples
Source: Diagram by the authors

include measurable energy reductions (Amsterdam), decreased congestion and improved response times (Barcelona, Singapore), and enhanced flood prediction and climate resilience (Copenhagen). Their operational maturity distinguishes them from emerging or experimental AI initiatives that lack demonstrable long-term effectiveness.

2.5. Conceptual completeness and analytical coherence

Together, the four cases encompass the main domains through which AI contributes to sustainable urbanism: Virtual Singapore addresses urban planning and governance; Barcelona highlights mobility and infrastructure integration; Amsterdam focuses on energy transition; and Copenhagen exemplifies water management and climate resilience. Collectively, they offer a coherent analytical framework that captures the multi-scalar, interdisciplinary, and systemic nature of AI's urban influence.

Regarding limitations, the study excludes cities such as Dubai, Toronto, and Shenzhen for several reasons: (i) Many initiatives in these contexts remain in early pilot stages or lack transparent, peer-reviewed data; (ii) cases such as Sidewalk Toronto were overshadowed by ethical and governance controversies, thereby limiting their suitability for assessing AI-driven sustainability; and (iii) other cases, including Dubai's Smart City strategy or Shenzhen's AI corridors, prioritize innovation branding and economic performance over integrated sustainability frameworks.

Consequently, the selected four cases provide a more balanced combination of demonstrated impact, reliable evidence, and alignment with sustainability objectives, making them appropriate for a systematic comparative examination of AI's role in urban development.

3. Digital intelligence in urban development

Urban planning and design, urban mobility, waste, energy, and water management are domains in which smart technologies can support more sustainable urbanism.

3.1. Digital integration in urban planning: Digital twins, GIS, and BIM

The complexity of contemporary urban challenges, ranging from climate resilience to sustainable densification, requires a shift toward more dynamic planning and design methodologies. The integration of building information modeling (BIM), geographic information systems (GIS), and digital twins is central to this transition, supporting a move from static two-dimensional planning to four-dimensional simulations that incorporate both spatial and temporal dynamics. This integrated approach enables holistic, predictive, and collaborative frameworks for sustainable urban development.

Although BIM, GIS, and digital twins each enhance urban intelligence individually, their full potential emerges through interoperability (OGC Urban Digital Twin Domain Working Group, 2024). Integrated dashboards play a key role by consolidating data visualization, analysis, and decision support into a single interface. These dashboards function as real-time operational control panels, enabling planners, engineers, and policymakers to coordinate across design and management phases (Biggs *et al*., 2022).

Within this interconnected system, BIM contributes detailed building-level information such as material performance, occupancy, and energy demand, whereas GIS situates these data within broader ecological, infrastructural, social, and economic landscapes. The digital twin then synchronizes these composite datasets with live IoT inputs (e.g., traffic flow, air quality, temperature, energy consumption) (Sacoto-Cabrera *et al*., 2025), generating a continuously updated representation of urban performance (Miller *et al*., 2021).

Dashboards serve as the cognitive interface for this ecosystem, presenting multisource data in a coherent and interactive format. For instance, a single dashboard may display real-time energy consumption from BIM, overlay spatial heat maps from GIS, and simulate future energy scenarios through the digital twin. This allows decision-makers to test interventions such as green roofs or traffic rerouting virtually before implementation (Mazzetto, 2024). Such dashboard-driven integration supports a predictive and adaptive four-dimensional urban management approach, improves cross-departmental coordination, and strengthens evidence-based governance aligned with sustainability and resilience objectives.

BIM provides rich, object-oriented three-dimensional (3D) models that capture the physical and functional characteristics of individual buildings. Its value is amplified when integrated with GIS, as seen in Singapore's virtual twin, where BIM data for new developments is embedded within the city's wider urban context. This enables precise analyses of shadows, wind flow, and energy performance within specific microclimates, ensuring alignment with sustainability goals (Dembski *et al*., 2020).

In contrast, GIS offers the spatial framework necessary for understanding urban systems. By mapping topography, infrastructure, demographics, and environmental conditions across multiple layers, it supports tasks such as suitability modeling for locating amenities or energy installations. For example, Amsterdam employs GIS to manage subterranean utilities, thereby reducing risks and conflicts during construction (Batty, 2018).

The digital twin synthesizes these capabilities into a dynamic virtual environment that updates continuously with real-time data. It enables predictive planning and scenario testing, as demonstrated by Singapore's Virtual Singapore platform, which supports simulations of emergency evacuations, drone route optimization, and thermal comfort modeling (Ketzler *et al*., 2020). Helsinki's open-access digital twin similarly enhances public engagement by enabling users to visualize proposed developments within their actual surroundings.

Together, BIM, GIS, and digital twins constitute a cohesive framework for evidence-based urban decision-making. BIM provides granular asset-level insight, GIS supplies essential spatial context, and digital twins add real-time operational intelligence and simulation capability. Their integration supports more efficient management of traffic, energy systems, climate adaptation, and equitable urban development.

3.2. Digital integration in smart urban mobility

The accelerating pace of global urbanization demands a fundamental shift from fragmented and inefficient networks toward interconnected, intelligent, and sustainable models. This transition is driven by the integration of IoT sensors, global positioning system (GPS), cameras, and mobile applications, which together create a data-driven mobility ecosystem. Such systems optimize infrastructure performance, manage demand in real time, and prioritize user-centered solutions that reduce congestion, enhance safety, and lower environmental impacts (Jasim *et al*., 2024).

IoTs sensors form the backbone of intelligent transport systems. Embedded in both infrastructure (Awad *et al*., 2019) and vehicles, they generate continuous data on traffic volume, speed, structural conditions, and environmental factors. Singapore's "Smart Nation" initiative exemplifies this approach, using an extensive sensor network to monitor traffic and operate an adaptive signal system that adjusts timings dynamically to ease congestion (Zanella *et al*., 2014). Barcelona uses similar sensor-enabled parking systems to reduce search times and associated emissions.

Moreover, GPS technology adds a critical layer of mobility tracking and optimization, especially for public transport and shared mobility services. In London, GPS data from buses support real-time arrival information and prevent bus bunching through algorithmic adjustments, improving service reliability. GPS also underpins mobility-as-a-service platforms such as Whim in Helsinki, which integrate multiple transport modes into a single interface to reduce dependence on private cars (Eckhardt *et al*., 2017).

Cameras and computer vision enhance this ecosystem by providing automated visual monitoring. In Dubai, AI-enabled cameras detect traffic violations to improve safety, while Hangzhou's "City Brain" uses video analytics to identify incidents and automatically adjust traffic signals to mitigate congestion (Batty, 2018). These capabilities signal a shift from manual supervision to predictive, automated management.

Mobile applications operate as the main point of interaction between citizens and the smart mobility system. Platforms such as Moovit and Citymapper integrate diverse data sources to deliver optimized routes and real-time travel updates. They also enable participatory data collection, allowing users to report disruptions and helping improve overall system responsiveness and accuracy (Allam & Dhunny, 2019).

3.3. Smart urban waste: Radio-frequency identification (RFID), GPS, and IoT integration

The escalating challenge of municipal solid waste management poses significant risks to public health, environmental sustainability, and municipal budgets in rapidly growing urban areas. In response, cities are increasingly adopting technologically integrated systems—such as RFID, GPS, and IoT—to shift from static, schedule-based waste collection to more dynamic, efficient, and sustainable models. These tools support a data-driven approach that enhances logistical performance, reduces environmental impacts, and strengthens public engagement.

IoTs sensors, including ultrasonic fill-level monitors, form the core of intelligent waste systems by providing real-time data on bin capacity. This data enables a transition from fixed collection schedules to demand-responsive operations. In Seoul, for instance, sensors relay bin-level information to an analytics platform that predicts fill rates and optimizes routes, resulting in a 20 percent reduction in collection costs and emissions (Lakhouit, 2025). Such systems reduce unnecessary trips while preventing overflow of wastes and related public health issues.

Furthermore, RFID technology adds precision and accountability to waste stream management. By assigning a unique identifier to each bin—linked to a household or business— municipalities can track disposal events and, when paired with weighing mechanisms, measure waste quantities. This supports incentive-based pricing structures, as seen in Milan, where residents are charged according to the weight of unsorted residual waste. The approach has significantly increased recycling rates and reduced landfill disposal by encouraging more sustainable behavior. RFID data also provides municipalities with detailed insights into neighborhood-level waste generation, improving both operational planning and policy decisions (Elechi *et al*., 2021; Prata *et al*., 2025).

The GPS systems further enhance operational efficiency by enabling real-time monitoring of collection vehicles. When combined with sensor and RFID data, GPS tracking supports dynamic route adjustments in response to traffic conditions or bin alerts. Cities such as Barcelona and Copenhagen use this integration to reduce idling, lower fuel consumption, and improve service responsiveness (Neto *et al*., 2024). These improvements contribute directly to reduced carbon emissions and operating costs.

The full value of these technologies emerges when they are integrated into a centralized data platform. AI can then analyze combined sensor, RFID, and GPS inputs to predict waste patterns, optimize fleet deployment, and advance circular economy initiatives. Amsterdam's "Waste Streams" program demonstrates this capability, using data analytics to improve resource recovery and support more effective material lifecycle management.

3.4. Digital energy integration in urban systems

The transformation of the traditional, centralized electrical grid into an intelligent and responsive network is fundamental to the decarbonization and efficient management of energy within sustainable urbanism. This shift is achieved through the integration of smart grids, smart meters, and IoT sensors, which together enable a data-driven approach to optimize generation, distribution, and consumption in real time (Jasim *et al*., 2024). This enhances resilience, integrates renewable sources, and reduces the urban carbon footprint.

The smart grid forms the overarching architecture of this new energy paradigm. Enhanced with digital communication and control technologies, it facilitates two-way flows of electricity and information, allowing the grid to respond dynamically to changes in supply and demand. For example, Singapore's Intelligent Energy System pilot employs advanced sensors and switches to enable self-healing capabilities; the system can automatically detect faults, isolate affected segments, and reroute power to minimize outages, thereby significantly improving service reliability (Zhang, 2024).

Smart meters function as critical nodes between utilities and consumers, providing granular, real-time consumption data that moves beyond monthly estimations. In London's Barking Riverside, smart meters supply residents with detailed usage insights through in-home displays and mobile applications. This transparency encourages behavioral change, enabling consumers to reduce consumption during peak, carbon-intensive periods. In addition, the data facilitates dynamic time-of-use pricing, incentivizing off-peak usage and flattening the load curve, which improves grid efficiency and defers the need for new peak-time power plants (Darby, 2010).

The IoT sensors complete the ecosystem by providing device-level intelligence. Embedded in buildings, streetlights, and renewable installations, they collect extensive data on environmental and operational conditions. In Barcelona, IoT-equipped streetlights adjust brightness based on ambient light and pedestrian presence, reducing energy waste. Similarly, sensors in buildings monitor occupancy and environmental factors, allowing building management systems to automate heating, cooling, and lighting for optimal efficiency without compromising comfort (Gaur *et al*., 2019).

The convergence of these technologies enables the effective integration of distributed energy resources. Smart inverters on solar panels, communicating via IoT networks, allow excess power to be fed back into the grid. Amsterdam's Smart City initiative exemplifies this through virtual power plants, where households with solar panels and batteries are aggregated into a controllable entity that can supply power during peak demand. This transformation repositions consumers as "prosumers," fostering a more flexible, resilient, and democratic energy system (Cui *et al*., 2021; Pasetti, 2018).

3.5. Digital water solutions for urban sustainability

Sustainable water resource management has become a pressing priority for urban developments increasingly strained by population growth, climate change, and aging infrastructure. A shift is taking place from reactive, fragmented governance to a proactive and integrated model supported by smart digital technologies. The combined use of smart water meters, acoustic sensors, and satellite imagery enables the creation of intelligent hydrosystems designed to minimize losses, improve efficiency, and strengthen long-term water security.

Smart water meters form the foundation of effective demand-side management and consumer engagement. By providing continuous, high-resolution consumption data and transmitting readings automatically, they replace estimated billing with precise, real-time insights. In Sabadell, Spain, a citywide smart metering initiative identified numerous small, continuous leaks by detecting baseline flows during periods when usage should be zero. The system also allows residents to access detailed consumption information through digital platforms, empowering them to conserve water and participate in demand-response measures. These efforts have led to measurable reductions in overall water use (Cominola *et al*., 2015). Such granular data is essential for accurate demand forecasting and conservation planning.

Acoustic sensors complement these efforts by strengthening the integrity of distribution networks. Attached directly to pipes, these IoT devices continuously listen for acoustic signatures associated with leaks. Advanced algorithms then analyze the data to locate leaks with high accuracy, before they escalate into major failures. Thames Water in London uses correlating acoustic sensors to identify and repair leaks more efficiently, significantly reducing non-revenue water while preventing costly service disruptions and infrastructure damage (Fan *et al*., 2022). Incorporating such technologies into new developments ensures long-term system reliability and operational resilience.

Satellite imagery and remote sensing add a broader, macro-scale perspective to urban water management. Using tools such as synthetic aperture radar and multispectral imaging, satellites monitor ground subsidence risks, reservoir storage, vegetation stress, and groundwater depletion. Chennai, India, has used satellite-derived data to track reservoir levels and identify critical zones of aquifer decline, providing essential information for citywide resource planning (Sheffield *et al*., 2018). This synoptic viewpoint supports integrated water resource management by linking local urban systems to regional hydrological conditions.

The integration of these technologies into a centralized data platform represents the emerging model for urban water governance. Smart meters detect endpoint anomalies, acoustic sensors locate distribution losses, and satellite systems monitor broader environmental dynamics. Together, they create an intelligent, closed-loop network in which information flows seamlessly from source to tap, enabling more efficient, resilient, and sustainable urban water management.

4. Global case studies and insights

In this section, Virtual Singapore, Barcelona's integrated IoT system, Amsterdam's City-Zen project, and Copenhagen's AI-driven hydrological management will be examined to derive comparative and empirical insights.

4.1. Virtual Singapore: A digital governance paradigm

The global progression of smart urbanism has moved beyond isolated technological interventions toward the creation of integrated digital ecosystems that mirror and inform the physical city (Townsend, 2013). Central to this evolution is the urban digital twin—a dynamic virtual model continuously synchronized with real-time data from its physical counterpart.

Singapore's "Virtual Singapore" represents one of the most advanced and comprehensive examples of this innovation. By integrating a detailed 3D city model with live information on traffic, weather, and energy use, it operates not merely as a visualization interface but as a powerful tool for simulation, planning, and governance, setting a global benchmark for contemporary urban management.

Virtual Singapore is built on a semantically rich 3D model of the entire city-state, as shown in Figure 2, incorporating terrain, infrastructure, and buildings through the integration of BIM and GIS. This digital foundation is continuously updated with live data from extensive IoT sensor and camera networks covering traffic, environmental conditions, and energy consumption (Ketzler *et al*., 2020). Its primary strength lies in its capacity for advanced analytics and scenario modeling.

The platform supports simulations of emergency crowd movement, optimizes 5G antenna placement, and models microclimatic impacts of new developments to mitigate urban heat island effects (Dembski *et al*., 2020). These capabilities allow planners to evaluate interventions before implementation, thereby reducing risks and enhancing resilience.

Singapore's initiative is part of a broader global shift toward urban digital twins, with cities adopting diverse approaches to meet their strategic priorities. Helsinki has developed an open-access 3D model that facilitates public participation and supports energy planning, emphasizing transparent data-sharing as a foundation for sustainable development (WGIC Council, 2024). Shanghai uses its digital twin for real-time traffic coordination and the management of major infrastructures, demonstrating its effectiveness in handling complex and large-scale urban systems (Yu *et al*., 2023).

In Jaipur—in the northwestern Indian state of Rajasthan—a digital twin has been applied in master planning to test future growth scenarios and assess their implications for transport and water resources, highlighting its value as a decision-support tool for rapidly expanding cities (Peldon *et al*., 2024).

Collectively, these international examples show that digital twins function not only as sophisticated models but as collaborative platforms that integrate diverse urban data streams. By integrating static 3D models, real-time IoT inputs, and predictive analytics, they provide a shared evidence base that connects engineers, planners, scientists,

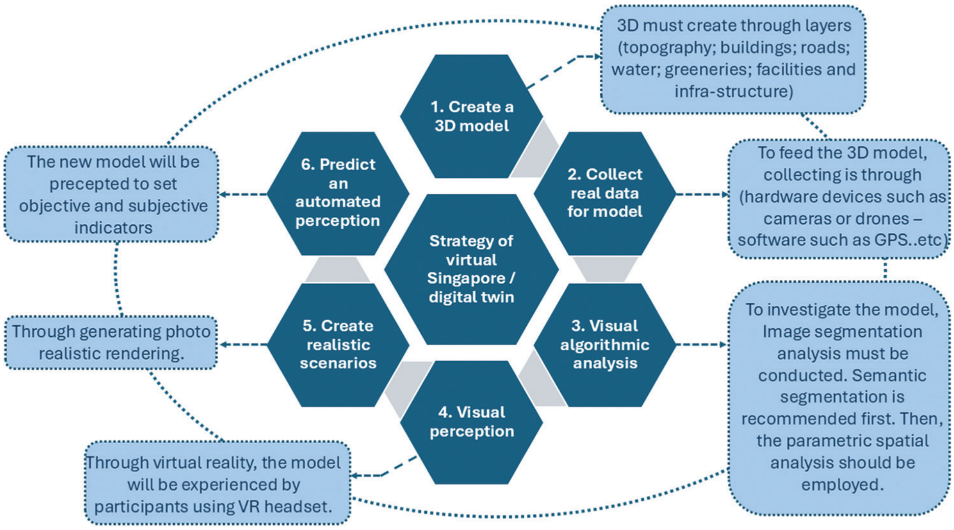

Figure 2. Strategic steps implemented in Virtual Singapore. Image created by the authors
Abbreviations: 3D: Three-dimensional; GPS: Global positioning system; VR: Virtual reality

and emergency services. This convergence facilitates a shift from reactive governance to proactive, data-driven management. This approach is exemplified by Virtual Singapore's ability to navigate and optimize the complex interdependencies of urban systems.

4.2. Barcelona: IoTs–driven urban management

The development of smart cities has progressed from isolated technological initiatives to integrated, citywide systems that use data to enhance urban performance and sustainability. Barcelona is a leading example of this transition, having established a comprehensive IoT network that captures and analyzes data across multiple sectors. This system—covering noise, air quality, traffic, pedestrian activity, and waste—has shifted the city's governance approach from reactive management to proactive, evidence-based decision-making (Hassan & Awad, 2018), providing a model that many cities now seek to emulate.

Barcelona's strategy stands out for its emphasis on foundational infrastructure and cross-sector integration. Early investments in a fiber-optic network and multifunctional (e.g., smart lampposts equipped with sensors, Wi-Fi, and connectivity points) created a robust backbone for large-scale IoT deployment (Bakıcı *et al*., 2013). This infrastructure supports diverse data streams: environmental sensors track air pollution and noise; traffic sensors manage vehicle flow; and pedestrian counters guide the design of public spaces.

The city's smart waste management system, which uses ultrasonic fill-level sensors to enable dynamic collection routes, has reduced fuel use, operating costs, and street litter (Gaur *et al*., 2019). The strength of this model lies not only in distributed sensors but also in the centralized platform that connects datasets, revealing relationships such as the link between congestion and localized pollution.

Other global smart cities reflect similar approaches while pursuing different priorities. Singapore's "Smart Nation" initiative extends IoT integration into domestic and social spheres, incorporating elderly health monitoring and digital citizen engagement as part of a broader vision of a sensorized society (Leong *et al*., 2024). Copenhagen leverages its IoT network to support its carbon neutrality goals, integrating data from weather stations, traffic systems, and building energy meters to dynamically model citywide energy use and emissions (Jensen *et al*., 2019). In contrast, the Atlanta BeltLine demonstrates a focused application, using IoT sensors to track pedestrian and cyclist activity along a key corridor to inform public space programming and maintenance (Georgia Tech Center for Advanced Communications Policy, 2021).

Together, these examples highlight a crucial shift: the real value of smart city systems lies not in data collection alone but in generating actionable intelligence. The main challenge is increasingly one of governance rather than technology, requiring sophisticated analytics and coordination across municipal departments. Barcelona's early experiences also underscored the importance of transparency and public trust in data governance. These experiences have shaped later initiatives, particularly under stringent regulatory frameworks such as the General Data Protection Regulation.

4.3. Copenhagen's AI approach to water resilience

As climate change accelerates the global hydrological cycle, cities face increasing risks from extreme rainfall and flooding. Traditional stormwater systems that were built for past climate conditions are no longer adequate. In response, many urban centers are adopting advanced computational tools to strengthen adaptive capacity. Copenhagen, Denmark, is a global frontrunner in this shift, using AI to model and manage stormwater runoff, thereby transforming its water infrastructure into a dynamic, intelligent system. This approach marks a significant evolution in urban planning, using predictive analytics to reduce flood risk and offering a transferable model for climate-resilient urban development (Lund *et al*., 2019).

Copenhagen's strategy emerged after a destructive cloudburst in 2011. The resulting Cloudburst Management Plan (C40, 2016) is supported by an AI-enhanced digital twin of the city's drainage network. This virtual model incorporates real-time data from IoT sensors measuring rainfall, sewer and canal water levels, and groundwater conditions (ClimateFit HEU, 2024). Machine learning algorithms then combine these live inputs with high-resolution weather forecasts to predict when, where, and how severely flooding may occur.

This predictive capability enables pre-emptive action; for example, the system can determine when to lower water levels in storage tunnels and retention basins ahead of a storm to maximize capacity and prevent overflow (Salih *et al*., 2025). This shift from reactive to anticipatory management has become a core principle of next-generation water resilience, optimizing infrastructure performance while enhancing public safety.

The broader role of AI in hydrological resilience lies in its ability to analyze complex environmental datasets and improve prediction accuracy across diverse water systems. Before applying AI in specific regional contexts, it is necessary to consider the modeling techniques involved. AI-driven hydrological models integrate satellite imagery, remote sensing data, and machine learning outputs to analyze rainfall behavior, flood dynamics, and soil moisture variability (Wani *et al*., 2024). These capabilities support early warning systems for both floods and droughts, strengthening decision-making and long-term adaptive planning in water management (Mak, 2025).

While AI offers powerful tools for interpreting multidimensional datasets and forecasting climate-related risks, its effectiveness depends on addressing challenges such as model transparency, data quality, and the integration of human behavior alongside ethical governance. Recent studies emphasize that AI can be transformative for climate resilience, but only when deployed within inclusive, transparent, and adaptive management frameworks (Mehryar *et al.*, 2024).

Globally, cities are adopting AI-driven hydrological systems to meet local needs. Singapore's national water agency employs machine learning models that process radar-based rainfall predictions and sensor data to forecast drainage capacity, automate pump and tidal gate operations, and issue early flood alerts (Gacu *et al*., 2025). Rotterdam uses a digital twin to manage its multifunctional water squares, applying AI to determine when to store or release stormwater while maintaining public space usability. In Surat, India, an AI-powered early warning system integrates meteorological data, river levels, and industrial schedules to forecast flooding along the Tapi River, facilitating timely evacuations and the protection of critical infrastructure (Bhat *et al*., 2013).

Collectively, these examples show that although specific applications vary, the underlying principle is consistent: AI adds a cognitive layer that enables cities to interpret complex hydrological data and implement preventive measures. However, they also highlight key challenges, including the high cost of sensor networks, the need for substantial computational resources, and the importance of coordinated governance to effectively act on AI-generated insights.

4.4. Amsterdam's City-Zen: AI-driven urban energy transition

The global transition to sustainable energy systems is particularly complex in urban environments, where high demand and interdependent infrastructure necessitate systemic optimization rather than incremental improvements. Amsterdam's City-Zen project exemplifies this approach by leveraging AI and data analytics to develop an intelligent thermal grid that optimizes energy use at the district level. This initiative demonstrates AI's role as a critical enabler of the urban energy transition, integrating diverse sources and fluctuating demand to maximize efficiency and renewable integration.

Focused on technological innovation and citizen engagement, the project established a smart thermal grid connecting buildings, renewable sources, and thermal storage. AI algorithms analyze multivariate datasets—including weather forecasts, historical consumption patterns, real-time thermal demand, and renewable availability—thereby enabling predictive optimization of production, storage, and distribution. For example, the system pre-heats water during periods of high solar generation or low electricity prices, flattening demand curves and reducing reliance on fossil-fuel peak boilers (Wei *et al*., 2024). This transforms the energy grid from passive infrastructure into an active, intelligent marketplace for local energy exchange.

This AI-centric model reflects a broader global recognition of the value of computational intelligence in managing complex energy systems. In Helsinki, a similar AI platform optimizes district heating by predicting demand based on weather and building data, reducing energy waste (Vakhnin *et al*., 2024). The Brooklyn Microgrid project in New York employs AI and blockchain to enable peer-to-peer energy trading, allowing residents with solar panels to trade excess energy autonomously (Mengelkamp *et al*., 2018). In Singapore, AI forecasts solar generation to maintain grid stability amidst renewable intermittency.

These examples underscore AI's role as a central orchestrator of future distributed energy systems, managing renewable intermittency, enabling prosumer markets, and unlocking systemic flexibility. However, projects like City-Zen also highlight enduring challenges, including data privacy, the need for resilient digital infrastructure, and the imperative of equitable benefit distribution.

5. Discussion

AI paradigms increasingly demonstrate substantial potential to advance sustainable urban development. A well-known example is Google's application of machine learning to optimize cooling operations within data centers by modeling relationships among sensor-derived variables such as cooling settings, temperatures, and server loads. This approach has enabled fine-tuned system control and significant energy savings (Evans & Gao, 2016), illustrating how AI can reduce energy consumption and carbon emissions—key objectives of environmental and economic sustainability.

AI applications have gained increasing interest in urban environmental governance. Machine learning techniques now support short-term air quality prediction (Komarudin *et al*., 2025; Mak & Lam, 2021), enabling targeted health advisories for vulnerable populations and informing traffic authorities in rerouting vehicles to mitigate pollution levels (Xu *et al*., 2025). In urban mobility systems, AI-enhanced traffic management improves network efficiency by adjusting signal timings based on real-time data flows. Notably, the "City Brain" initiative in Hangzhou has reduced congestion in its preliminary phase, thereby lowering fuel consumption and emissions.

At the metropolitan scale, the Virtual Singapore project integrates AI-driven analytics with advanced simulation tools to evaluate prospective urban development scenarios—including infrastructure performance, land-use configurations, energy optimization, and climate adaptation—prior to implementation (Shirowzhan *et al*., 2020). By facilitating evidence-based decision-making and accelerating governance processes, the project foregrounds the growing role of AI in addressing complex, multi-sectoral urban challenges. Collectively, such initiatives reinforce the economic and environmental pillars of sustainable development, while the social dimension remains relatively underexplored.

Despite these achievements, AI-enabled urban platforms such as Virtual Singapore encounter several structural and ethical challenges. Managing large volumes of personal and infrastructural data raises significant privacy and security concerns, necessitating robust governance frameworks to maintain public trust. Ensuring data consistency and accuracy across multiple institutional sources remains technically demanding and essential for reliable simulations. Social inclusivity is also at risk due to digital divides in access and literacy, while algorithmic bias and opaque decision-making processes underscore the need for stronger ethical oversight.

Comparable limitations have emerged in other cities experimenting with AI, such as Barcelona, where high initial investment costs, integration difficulties with legacy infrastructure, and persistent concerns regarding data protection have hindered progress.

In the Netherlands, AI has become a central component of municipal smart-city strategies (Van Zoonen, 2022), with numerous large-scale applications deployed across Amsterdam, The Hague, and Eindhoven. In The Hague's Scheveningen district, for instance, a machine learning-based crowd safety manager forecasts visitor flows using more than 30 variables—including meteorological data and scheduled events—thereby enabling proactive public space management (Giest *et al*., 2025). In Amsterdam's NDSM district, AI-enabled cameras conduct anonymous footfall analyses to evaluate visitation patterns while safeguarding privacy (Wray, 2021).

Amsterdam also employs advanced large language models integrated with retrieval-augmented generation to process citizen complaints related to waste management, street maintenance, and other municipal services. By cross-referencing administrative databases, the system can deliver automated responses when resolutions are underway or when requests fall outside policy boundaries, thereby reducing administrative workloads and improving citizen experience (Meijer & Thaens, 2020). Alzahrani *et al*. (2025) reported that employing IoT paradigms in waste management helps reduce overall waste-management costs, lowers landfill dependency by 30 percent, and increases recycling efficiency to 90 percent.

In public safety, Eindhoven utilizes multi-camera computer vision systems to anonymously track movement trajectories and identify anomalous behavior indicative of potential criminal activity (Joh, 2019; Martin *et al.*, 2022). Environmental monitoring has also benefited from AI-based prediction: The Hague's smart energy system forecasts neighborhood-level energy demand and local renewable production to optimize grid performance (Hajer & Dassen, 2019), while Amsterdam's Green Mile initiative leverages sensors and AI to detect air-quality and noise anomalies, enabling residents to advocate targeted environmental interventions (I amsterdam, 2023).

The use of AI extends to port operations and water quality management as well. In The Hague, image recognition technologies support the automated classification and registration of vessels (Mohan & Hellwich, 2023), whereas Amsterdam deploys sensor networks to monitor water quality in public swimming areas, with real-time data made accessible to the public (Meyers *et al.*, 2022).

The Copenhagen Accord underscores potential political and structural constraints in scaling AI for climate resilience. The accord's failure to establish a binding climate treaty highlights challenges that parallel contemporary AI deployment, including: (i) Political inertia, where insufficient consensus on governance, funding, and data-sharing may impede AI adoption; (ii) equity and justice issues, given that algorithmic biases and unequal digital access could reproduce global and local inequalities; and (iii) inadequate mechanisms for technology transfer, which similarly constrain the ability of developing countries to adopt AI-based climate resilience tools due to limited digital infrastructure and technical capacity.

Smart city initiatives are prone to failure when they prioritize technological solutions over comprehensive planning, transparent regulatory frameworks, and the social legitimacy required for sustainable urban development. In Toronto's sidewalk project, the absence of clear data-ownership arrangements and inadequate protection of residents' privacy generated substantial public opposition, demonstrating that technologically intensive urban planning cannot succeed without strong civic accountability (Austin & Lie, 2021). Urban planning scholars have further observed that the project exemplified an over-reliance on corporate-driven technological interventions, pursued at the expense of incremental, community-centered urban development (Kollar, 2022; Flynn & Valverde, 2019). This approach raised significant concerns regarding the commodification of public space and the erosion of social and spatial equity (Shimizu *et al.*, 2022).

6. Conclusion

The Dutch experience with smart urbanism demonstrates that the success of AI-enabled cities depends not only on technological sophistication but, critically, on the governance frameworks that shape their development. Approaches such as the Living Labs, Privacy by Design, and participatory ethical principles illustrate how innovation can be aligned with public values while ensuring transparency and legitimacy (Cavoukian, 2011; Van Zoonen, 2022). These insights are particularly relevant for cities like Copenhagen, where the ambition to expand AI-driven systems intersects with challenges related to energy demand, data infrastructure, and social inclusion.

This study highlights that advancing sustainable, equitable, and resilient urban futures requires a coordinated, multidimensional strategy for integrating AI into the built environment, where a strong correlation exists between sustainability and smart cities (Gu *et al.*, 2025). Six interrelated principles—(i) human-centered design; (ii) environmental sustainability through ecological planning approaches (Mersal, 2016); (iii) evidence-based planning; (iv) system-wide integration; (v) predictive and prescriptive analytics, and (vi) participatory governance (Gao *et al.*, 2020)—form a holistic framework for guiding this transition. Together, they mitigate risks associated with digital inequality, infrastructural fragmentation, and institutional inertia (Son *et al.*, 2023), while supporting more adaptive, citizen-centered urban systems (Farhan *et al.*, 2025).

The growing application of AI and information and communication technology across planning, mobility, waste, energy, and water management demonstrates their capacity to enhance efficiency, sustainability, and urban liveability (Allam & Dhunny, 2019; Bibri & Krogstie, 2017; Chi & Mak, 2021). However, the expansion of their role underscores the growing need for robust ethical governance. Transparent, accountable, and inclusive oversight is essential to prevent algorithmic bias, curb disproportionate surveillance, and ensure that AI systems align with democratic values (McCrory, 2024; Winfield & Jirotka, 2018).

Ultimately, the future of AI-enabled urbanism depends on cities' capacity to balance technological opportunity with social responsibility. By embedding ethical principles, fostering public participation, and integrating systems in ways that support both sustainability and resilience, cities can leverage AI not as an end in itself but as a tool for advancing equitable and adaptable urban futures.

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