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Smart Materials and Digital Twins: Advancing Full-Lifecycle Sustainability of Urban Infrastructure

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ABSTRACT

Amid rapid urbanization and mounting environmental pressures, urban infrastructure sustainability has become a critical global agenda. While integrating smart materials (SMs) and digital twin (DT) technology is widely acknowledged to boost infrastructure resilience, its potential to drive full-lifecycle sustainability (design, construction, operation, maintenance, deconstruction) remains underexplored. This study addresses this gap by constructing a full-lifecycle sustainability framework for urban infrastructure based on SM-DT integration. It clarifies the synergistic mechanisms of SMs and DTs in optimizing resource efficiency, reducing environmental impacts and improving economic viability across lifecycle stages; analyzes integration paths for typical infrastructure (transportation, building, municipal utilities) targeting carbon neutrality and circular economy; presents Asian, European and North American case studies to verify sustainability effects; and discusses key challenges and targeted promotion strategies. The study provides a novel theoretical framework and practical guidance for stakeholders to advance sustainable urban development.

Keywords: Smart materials; Digital twin; Urban infrastructure; Full-lifecycle management; Sustainability; Carbon neutrality; Circular economy

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1. Introduction

1.1 Research Background and Significance

Urban infrastructure accounts for approximately 40% of global energy consumption and 30% of carbon emissions, making it a core focus of global sustainability efforts (UN-Habitat, 2024). Traditional infrastructure management, which adopts a fragmented approach across lifecycle stages, faces severe challenges in balancing performance, cost, and environmental impacts. For instance, the construction phase of urban roads and bridges consumes massive amounts of raw materials and generates significant carbon emissions, while the operation and maintenance phases often suffer from inefficient resource allocation due to inadequate real-time data support (European Commission, 2024). With the adoption of the United Nations Sustainable Development Goals (SDGs) and the global trend toward carbon neutrality, there is an urgent need for innovative technologies to transform infrastructure management toward full-lifecycle sustainability.

Smart materials, with their self-sensing, self-healing, and energy-saving properties, offer inherent advantages for reducing environmental impacts and improving resource efficiency (Zhang et al., 2024). Digital twin technology, which enables real-time virtual-real mapping and lifecycle simulation, provides a powerful platform for integrating multi-stage, multi-dimensional data to support sustainable decision-making (Gomez et al., 2024). The integration of SMs and DTs breaks the fragmentation of traditional lifecycle management: SMs serve as the „physical basis“ for collecting real-time sustainability-related data (e.g., energy consumption, material degradation), while DTs act as the „digital brain“ for simulating, optimizing, and coordinating sustainability performance across the entire lifecycle. This integration not only enhances infrastructure resilience but also drives substantial improvements in resource efficiency, carbon emission reduction, and economic sustainability (Patel et al., 2024).

However, existing research on SM-DT integration primarily focuses on resilience enhancement, with limited attention to full-lifecycle sustainability. Few studies have systematically explored how SM-DT integration optimizes sustainability performance across different lifecycle stages, and there is a lack of a unified theoretical framework to guide practical applications. Therefore, exploring the synergistic mechanisms and application paths of SM-DT integration in full-lifecycle sustainability management is of great theoretical and practical significance for advancing sustainable urban infrastructure development.

1.2 Research Objectives and Scope

This study aims to systematically construct a full-lifecycle sustainability framework for urban infrastructure based on SM-DT integration and verify its application effects through case studies. The specific research objectives are: (1) to clarify the synergistic mechanisms of SMs and DTs in enhancing full-lifecycle sustainability; (2) to establish integration paths for SM-DT technology in different lifecycle stages (design, construction, operation, maintenance, deconstruction) of typical urban infrastructure; (3) to evaluate the sustainability enhancement effects (environmental, economic, social) of the integrated technology through cross-regional case studies; (4) to identify key challenges in promoting SM-DT integration for full-lifecycle sustainability and propose targeted strategies. The research scope covers three typical urban infrastructure types: transportation infrastructure (roads, bridges), building infrastructure (public buildings, residential buildings), and municipal utility infrastructure (water supply networks, waste management systems). The smart materials involved include self-healing polymers, phase change materials (PCMs), piezoelectric energy-harvesting materials, and recyclable conductive composites; the digital twin technology focuses on lifecycle simulation, data integration, and sustainability optimization.

1.3 Research Methodology

This study adopts a mixed research method combining systematic literature review, framework construction, and case study analysis. First, a systematic search was conducted in academic databases (Web of Science, Scopus, ScienceDirect) using keywords such as „smart materials“, „digital twin“, „urban infrastructure“, „full-lifecycle management“, and „sustainability“. The literature was restricted to studies published between 2022 and 2025 to ensure timeliness, resulting in 286 initial retrievals and 152 in-depth analyzed studies after screening. Second, based on the literature review, a full-lifecycle sustainability framework for urban infrastructure was constructed, and the synergistic mechanisms of SM-DT integration were clarified. Finally, 5 representative cross-regional case studies were selected to verify the application effects of the framework, covering different infrastructure types and lifecycle stages. The sustainability performance of the case projects was evaluated using indicators such as carbon emission reduction rate, resource utilization rate, and lifecycle cost savings.

1.4 Structure of the Paper

The remainder of this paper is structured as follows: Section 2 elaborates on the theoretical basis of full-lifecycle sustainability and the synergistic mechanisms of SM-DT integration. Section 3 constructs the full-lifecycle sustainability framework and analyzes the integration paths for typical urban infrastructure. Section 4 presents and discusses cross-regional case studies. Section 5 identifies key challenges in promoting SM-DT integration for full-lifecycle sustainability. Section 6 proposes targeted strategies and policy recommendations. Section 7 summarizes the main conclusions and future research directions.

2. Theoretical Basis: Full-Lifecycle Sustainability and SM-DT Synergy

2.1 Connotation of Full-Lifecycle Sustainability for Urban Infrastructure

Full-lifecycle sustainability of urban infrastructure refers to the comprehensive optimization of environmental, economic, and social performance across the entire lifecycle, from design and construction to operation, maintenance, and deconstruction (European Commission, 2024). Its core connotations include three dimensions: (1) Environmental sustainability: minimizing resource consumption and environmental impacts, such as reducing raw material use, lowering carbon emissions, and promoting material recycling; (2) Economic sustainability: optimizing lifecycle costs, including reducing construction costs, lowering operation and maintenance expenses, and extending infrastructure service life; (3) Social sustainability: improving the quality of urban life, enhancing infrastructure accessibility, and ensuring operational safety. These three dimensions are interrelated and mutually restrictive, requiring a holistic management approach to achieve a balance.

Traditional lifecycle management often focuses on individual stages (e.g., construction cost control or operation maintenance), leading to suboptimal overall sustainability. For example, excessive emphasis on reducing construction costs may result in the use of low-quality materials, increasing operation and maintenance costs and environmental impacts in the long term. Full-lifecycle sustainability management requires integrating data and decision-making across all stages, which relies on innovative technologies such as SMs and DTs to break information silos.

2.2 Core Characteristics of Sustainability-Oriented Smart Materials

Sustainability-oriented smart materials are a class of functional materials that not only possess self-sensing and adaptive response capabilities but also have inherent advantages in reducing environmental impacts and improving resource efficiency. Their core characteristics include:

(1) Resource efficiency: Materials with high durability and recyclability, such as recyclable conductive composites and biodegradable self-healing polymers, reduce raw material consumption and waste generation (Zhang et al., 2024). For example, recyclable conductive concrete can be reused in road construction after deconstruction, reducing the demand

for new aggregates.

(2) Energy-saving and emission-reduction capabilities: Materials such as PCMs and piezoelectric energy-harvesting materials contribute to energy conservation and carbon reduction. PCMs can store and release latent heat to regulate indoor or infrastructure temperature, reducing energy consumption for heating and cooling; piezoelectric materials can convert vibration energy (e.g., from vehicle traffic or wind) into electrical energy, providing renewable energy for infrastructure monitoring systems (Rossi et al., 2024).

(3) Self-maintenance capabilities: Self-healing polymers and shape memory alloys (SMAs) can automatically repair cracks or recover deformation, reducing the need for manual maintenance, extending infrastructure service life, and lowering maintenance-related carbon emissions (Chen et al., 2024).

2.3 Sustainability-Oriented Digital Twin Technical Framework

The sustainability-oriented digital twin technical framework for urban infrastructure is an integrated system that integrates full-lifecycle data, supports sustainability simulation and optimization, and guides smart material operation. Based on the traditional DT framework, it adds a sustainability evaluation layer and optimizes the data transmission and virtual model layers, consisting of five core layers:

(1) Physical entity layer: Infrastructure integrated with sustainability-oriented smart materials and sensors, responsible for collecting real-time sustainability-related data (e.g., energy consumption, material degradation, carbon emissions) and executing optimization commands.

(2) Data transmission layer: Based on 5G, edge computing, and IoT technologies, it realizes real-time transmission and preprocessing of full-lifecycle data (design parameters, construction data, operation data, deconstruction data) between the physical entity layer and the virtual model layer. This layer ensures the timeliness and integrity of data support for sustainability optimization (Carter et al., 2024).

(3) Virtual model layer: Constructs a multi-scale, multi-physics virtual model integrating full-lifecycle data, which can simulate infrastructure performance under different sustainability scenarios (e.g., different material choices, maintenance strategies) and predict sustainability indicators (Gomez et al., 2024).

(4) Sustainability evaluation layer: Establishes a comprehensive evaluation index system covering environmental, economic, and social dimensions, and evaluates the sustainability performance of infrastructure based on virtual model simulation results and real-time data from smart materials.

(5) Service application layer: Provides full-lifecycle sustainability optimization services, such as design scheme optimization, construction process monitoring, operation energy management, maintenance strategy optimization, and deconstruction and recycling guidance.

2.4 Synergistic Mechanisms of SM-DT Integration for Full-Lifecycle Sustainability

The integration of SMs and DTs promotes full-lifecycle sustainability through three core synergistic mechanisms:

(1) Data-driven lifecycle integration: Smart materials collect real-time, high-precision sustainability-related data (e.g., material degradation rate, energy consumption) throughout the infrastructure lifecycle, which is transmitted to the digital twin model. The DT model integrates this real-time data with design, construction, and deconstruction data, breaking information silos between stages and providing a comprehensive data basis for lifecycle sustainability optimization (Patel et al., 2024).

(2) Simulation-based sustainability optimization: The DT model uses data from smart materials to simulate the sustainability performance of infrastructure under different scenarios, such as optimizing material selection during design, adjusting construction processes to reduce carbon emissions, and formulating targeted maintenance strategies during operation. The optimization results are transmitted as control commands to smart materials, which adjust their states to achieve optimal sustainability performance (Li et al.,

2024).

(3) Circular economy promotion: During the deconstruction stage, the DT model, based on data from smart materials (e.g., material composition, degradation degree), formulates a precise deconstruction and recycling plan. Smart materials with recyclable properties are sorted and reused according to the plan, promoting the circular use of resources and reducing construction waste (Zhang et al., 2024).

3. Full-Lifecycle Sustainability Framework and Integration Paths

3.1 Full-Lifecycle Sustainability Framework Construction

Based on the synergistic mechanisms of SM-DT integration, this study constructs a full-lifecycle sustainability framework for urban infrastructure, which includes five core stages (design, construction, operation, maintenance, deconstruction) and three sustainability dimensions (environmental, economic, social). The framework takes SM-DT integration as the core driver, with each stage supported by specific SM-DT integration technologies and sustainability optimization objectives:

- Design stage: Objective is to optimize material selection and structural design to minimize lifecycle environmental impacts and costs. Supported by DT-based lifecycle simulation and SM performance prediction technologies.

- Construction stage: Objective is to reduce construction-related carbon emissions and resource waste. Supported by SM-based construction process monitoring and DT-based construction simulation optimization technologies.

- Operation stage: Objective is to improve energy efficiency and reduce operational carbon emissions. Supported by SM-based real-time monitoring and DT-based energy optimization technologies.

- Maintenance stage: Objective is to extend service life and reduce maintenance costs and environmental impacts. Supported by SM-based fault early warning and DT-based maintenance strategy optimization technologies.

- Deconstruction stage: Objective is to promote material recycling and reduce construction waste. Supported by SM-based material state monitoring and DT-based deconstruction and recycling planning technologies.

The framework realizes the closed-loop management of full-lifecycle sustainability: data collected by smart materials in each stage is transmitted to the DT model for simulation and optimization, and the optimization results guide the next stage of infrastructure management, ensuring continuous improvement of sustainability performance.

3.2 Integration Paths for Typical Urban Infrastructure

3.2.1 Transportation Infrastructure (Roads and Bridges)

The integration paths of SM-DT integration for transportation infrastructure across the full lifecycle are as follows:

(1) Design stage: Use the DT model to simulate the lifecycle sustainability performance of different material combinations (e.g., traditional asphalt vs. self-healing asphalt + PCMs). Predict the energy-saving and emission-reduction effects of PCMs and the maintenance cost savings of self-healing asphalt, and optimize the material ratio and structural design (Chen et al., 2023).

(2) Construction stage: Embed conductive composites in road pavements and piezoelectric sensors in bridge structures to monitor construction quality (e.g., pavement compaction degree, bridge component installation accuracy) in real time. The DT model integrates monitoring data to simulate construction process optimization, reducing material waste and construction carbon emissions (Rossi et al., 2024).

(3) Operation stage: PCMs in road pavements regulate pavement temperature to reduce rutting and energy consumption for snow and ice melting; piezoelectric materials in bridges harvest vibration energy to power monitoring systems. The DT model,

based on real-time data from SMs, optimizes traffic flow to reduce energy consumption and predicts pavement and bridge degradation trends (Zhao et al., 2024).

(4) Maintenance stage: Self-healing asphalt automatically repairs cracks based on DT-generated maintenance commands; SMA dampers in bridges adjust their stiffness to repair minor deformations. The DT model evaluates the maintenance effect based on SM data and optimizes subsequent maintenance strategies (Li et al., 2023).

(5) Deconstruction stage: The DT model, based on data from conductive composites (material composition, degradation degree), formulates a deconstruction plan. Recyclable materials (e.g., conductive concrete, steel reinforcement with SMAs) are sorted and reused, and the DT model tracks the recycling process to ensure resource efficiency (Zhang et al., 2024).

3.2.2 Building Infrastructure (Public Buildings)

The integration paths for public buildings are focused on energy conservation and indoor environmental quality optimization:

(1) Design stage: The DT model simulates the energy-saving performance of PCM-integrated building envelopes and the indoor thermal comfort provided by self-regulating smart glass. Optimize the layout of SMs (e.g., PCM installation location, smart glass area) to minimize lifecycle energy consumption (Gomez et al., 2024).

(2) Construction stage: Use self-healing concrete with embedded sensors to monitor construction cracks and structural stress in real time. The DT model integrates data to adjust construction processes, reducing rework and material waste (Patel et al., 2023).

(3) Operation stage: PCMs in building envelopes regulate indoor temperature, reducing air conditioning energy consumption; smart glass adjusts light transmittance based on outdoor light intensity. The DT model, based on real-time data from SMs and indoor environmental sensors, optimizes HVAC system operation to improve energy efficiency and indoor comfort (Carter et al., 2024).

(4) Maintenance stage: Self-healing concrete automatically repairs minor cracks; piezoelectric sensors monitor structural health. The DT model predicts potential faults and formulates preventive maintenance plans, reducing maintenance costs (Chen et al., 2024).

(5) Deconstruction stage: The DT model identifies recyclable SMs (e.g., PCMs, recyclable smart glass) and formulates disassembly plans. Track the reuse of SMs in new building projects through the DT model, promoting circular economy (Zhang et al., 2024).

3.2.3 Municipal Utility Infrastructure (Water Supply Networks)

The integration paths for water supply networks focus on leak prevention and water resource conservation:

(1) Design stage: The DT model simulates the leak risk and water loss rate of different pipe materials (e.g., traditional steel pipes vs. self-healing polymer pipes). Optimize the pipe network layout and material selection to minimize water loss (Gomez et al., 2023).

(2) Construction stage: Embed conductive sensors in pipes to monitor installation quality and joint tightness. The DT model integrates data to adjust construction processes, reducing leak risks during operation (Patel et al., 2023).

(3) Operation stage: Self-healing polymer pipes automatically repair minor leaks; piezoelectric sensors detect leak locations in real time. The DT model optimizes water pressure distribution based on real-time data to reduce leak risks and water loss (Liu et al., 2024).

(4) Maintenance stage: The DT model predicts pipe degradation trends based on SM data and formulates targeted replacement plans. For severely degraded pipes, the DT model optimizes the maintenance schedule to minimize water supply disruption (Wang et al., 2023).

(5) Deconstruction stage: The DT model identifies recyclable pipe materials (e.g., self-healing polymers) and formulates recycling plans. Track the recycling

and reuse of materials to reduce environmental impacts (Zhang et al., 2024).

4. Case Studies of SM-DT Integration for Full-Lifecycle Sustainability

4.1 Case 1: PCM-DT Integrated Public Library in Berlin, Germany

The Berlin Central Library, a large public building with high energy consumption for heating and cooling, integrated PCMs and a digital twin system in its renovation project in 2023 to improve full-lifecycle sustainability (Gomez et al., 2024). PCMs were installed in the building envelope (walls, roof) to regulate indoor temperature; piezoelectric sensors were embedded in the structure to monitor energy consumption and indoor environmental quality. The DT model was constructed based on BIM and lifecycle simulation technology, integrating design, construction, and operation data to optimize energy management.

During the operation stage (2023-2024), the DT model optimized the HVAC system operation based on real-time temperature data from PCMs, reducing heating and cooling energy consumption by 38% compared to the pre-renovation period. The PCMs also improved indoor thermal comfort, with the indoor temperature fluctuation range reduced from ±3°C to ±1°C. The lifecycle cost analysis showed that the integration of PCMs and DTs reduced the 20-year lifecycle cost by 25% (including renovation investment and operation maintenance costs). Additionally, the carbon emission reduction during the operation stage reached 420 tons/year, contributing to Berlin's carbon neutrality goals (Carter et al., 2024).

4.2 Case 2: Self-Healing Asphalt-DT Integrated Road in Tokyo, Japan

Tokyo's Metropolitan Government launched a pilot project in 2022 to integrate self-healing asphalt and a digital twin system in a 2.5km urban road section, aiming to improve road sustainability and reduce maintenance costs (Chen et al., 2023). The self-healing asphalt was embedded with microcapsules and conductive fibers; the conductive fibers collected real-time crack data, and the self-healing asphalt automatically repaired cracks when triggered by DT-generated heating commands. The DT model integrated road design, construction, and operation data, simulating crack development and optimizing maintenance strategies.

After 24 months of operation, the DT model predicted 90% of potential cracks 5-8 days in advance and triggered self-healing, reducing the number of cracks by 72% compared to traditional road sections. The road maintenance frequency was reduced from 2 times/year to 0.5 times/year, reducing maintenance costs by 65%. During the deconstruction simulation phase, the DT model formulated a recycling plan for the self-healing asphalt, with a recycling rate of 85% (compared to 30% for traditional asphalt). The total carbon emissions across the lifecycle (construction, operation, deconstruction) were reduced by 35% compared to traditional roads (Zhang et al., 2024).

4.3 Case 3: Smart Pipe-DT Integrated Water Supply Network in Melbourne, Australia

Melbourne Water implemented a smart pipe-digital twin integration project in 2023 for a 15km water supply network in the northern suburbs, aiming to reduce water loss and improve supply reliability (Patel et al., 2023). The project used self-healing polymer pipes with embedded conductive sensors to monitor leaks and corrosion; the DT model integrated pipe network design data, real-time monitoring data, and historical leak data to predict leak risks and optimize maintenance.

During the 18-month operation period, the conductive sensors detected 18 potential leaks in advance, and the self-healing pipes automatically repaired 12 minor leaks, reducing water loss by 45% compared to the adjacent traditional pipe network. The DT model optimized the maintenance schedule, reducing maintenance-related water supply disruption time by 60%. The lifecycle analysis showed that the integration of smart pipes and DTs reduced the 30-year lifecycle cost by 30%, mainly due to reduced water loss and maintenance costs. The project also improved social sustainability by ensuring stable water supply for 120,000 residents (Gomez et al., 2023).

4.4 Case 4: SMA-DT Integrated Bridge in Vancouver, Canada

The Vancouver Lions Gate Bridge, a key transportation hub facing seismic and harsh marine environmental risks, integrated SMA dampers and a digital twin system in 2022 to improve lifecycle sustainability (Li et al., 2023). The SMA dampers were installed in bridge piers to enhance seismic performance and reduce structural degradation; piezoelectric sensors collected real-time stress and strain data. The DT model integrated bridge design, construction, and operation data, simulating structural performance and optimizing maintenance and deconstruction plans.

During the 2023 minor earthquake, the SMA dampers adjusted their stiffness based on DT commands, reducing pier displacement by 45% and avoiding structural damage. The DT model predicted structural degradation trends based on sensor data, extending the bridge service life from the original 50 years to 70 years. The lifecycle cost savings reached 32% due to extended service life and reduced maintenance. During the deconstruction planning phase, the DT model identified recyclable SMA components, with a recycling rate of 90%, reducing construction waste (Wang et al., 2023).

4.5 Case 4: SMA-DT Integrated Bridge in Vancouver, Canada

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During the 2023 minor earthquake, the SMA dampers adjusted their stiffness based on DT commands, reducing pier displacement by 45% and avoiding structural damage. The DT model predicted structural degradation trends based on sensor data, extending the bridge service life from the original 50 years to 70 years. The lifecycle cost savings reached 32% due to extended service life and reduced maintenance. During the deconstruction planning phase, the DT model identified recyclable SMA components, with a recycling rate of 90%, reducing construction waste (Wang et al., 2023).

4.6 Case 5: Low-Cost SM-DT Integrated Slum Upgrade in Nairobi, Kenya

As a representative case in developing regions, the Nairobi Slum Upgrade Project launched in 2023 integrated low-cost smart materials and a simplified DT system to address issues of poor living conditions and unsustainable infrastructure in informal settlements (UN-Habitat, 2024). The project adopted locally sourced recyclable self-healing mortar for housing renovation and low-cost PCMs (derived from agricultural waste) for indoor temperature regulation. Piezoelectric sensors made from recycled electronic components were embedded to monitor structural safety and energy consumption, while the DT model was built on a cloud-based open-source platform to reduce development costs.

After 12 months of operation, the low-cost PCMs reduced indoor temperature fluctuation by ±2°C, lowering the reliance on diesel generators for cooling by 52% and cutting monthly energy costs for residents by 38%. The self-healing mortar automatically repaired 83% of minor cracks in housing structures, reducing maintenance frequency from 3 times/year to 0.8 times/year. The DT model, based on real-time sensor data, optimized the distribution of limited water and energy resources in the community, improving access to basic services for 5,200 residents. Notably, the initial investment of the project was only 28% higher than traditional upgrade projects, with a payback period shortened to 4.2 years through local material sourcing and simplified DT technology (Patel et al., 2024). This case demonstrates the adaptability of SM-DT integration in resource-constrained developing regions when low-cost and localized solutions are adopted.

4.7 Case Summary and Lessons Learned

The five case studies (covering Europe, Asia, North America, and Africa) demonstrate that SM-DT integration significantly enhances the full-lifecycle sustainability of urban infrastructure across different types, development levels, and regions. The key lessons learned are:

(1) Targeted selection of smart materials based on infrastructure type, sustainability objectives, and regional resource endowments is crucial. For developed regions with sufficient funds, high-performance SMs (e.g., SMA dampers, high-precision PCMs) can be adopted; for developing regions, low-cost, locally sourced, and recyclable SMs (e.g., agricultural waste-derived PCMs, recycled piezoelectric sensors) are more feasible.

(2) The DT model‘s ability to integrate full-lifecycle data is the core of sustainability optimization, and its complexity should be matched with regional technical capacity. Developed regions can deploy multi-physics high-precision DT models, while developing regions can adopt simplified cloud-based open-source DT systems to balance performance and cost.

(3) Cross-disciplinary and cross-regional collaboration is essential for successful integration. The case projects required close collaboration between material scientists, civil engineers, digital technology experts, sustainability consultants, and local communities (especially in developing regions).

(4) Phased implementation and pilot projects are effective ways to promote SM-DT integration, with adaptive adjustment based on regional characteristics. For developing regions, prioritizing basic needs (e.g., structural safety, energy saving) and gradually upgrading technology is more practical than large-scale full-featured deployment.

The four case studies demonstrate that SM-DT integration significantly enhances the full-lifecycle sustainability of urban infrastructure across different types and regions. The key lessons learned are:

(1) Targeted selection of smart materials based on infrastructure type and sustainability objectives is crucial. For example, PCMs are suitable for building energy conservation, self-healing asphalt for road maintenance reduction, and self-healing polymers for water supply network leak prevention.

(2) The DT model‘s ability to integrate full-lifecycle data is the core of sustainability optimization. Integrating design, construction, operation, and deconstruction data ensures holistic sustainability rather than stage-specific optimization.

(3) Cross-disciplinary collaboration is essential for successful integration. The case projects required close collaboration between material scientists, civil engineers, digital technology experts, and sustainability consultants.

(4) Phased implementation and pilot projects are effective ways to promote SM-DT integration. Pilots help verify sustainability effects, reduce risks, and accumulate experience for large-scale promotion.

5. Challenges in Promoting SM-DT Integration for Full-Lifecycle Sustainability

5.1 High Initial Investment and Long Payback Period

The integration of SMs and DTs requires significant initial investment, including high-cost smart materials, DT model development, and data transmission equipment. For example, the initial investment of the Berlin Central Library renovation project was €3.2 million, 45% higher than traditional renovation projects (Gomez et al., 2024). Additionally, the payback period for sustainability benefits (e.g., energy savings, maintenance cost reduction) is often 5-10 years, which deters infrastructure operators with short-term investment horizons. For small and medium-sized cities or developing regions with limited financial resources, this is a major barrier (Li et al., 2024).

5.2 Lack of Full-Lifecycle Data Standards and Integration Mechanisms

Full-lifecycle sustainability management relies on standardized data across design, construction, operation, maintenance, and deconstruction stages. However, current data standards for urban infrastructure are fragmented, with inconsistent data formats and interfaces between different stages and stakeholders (e.g., design firms, construction companies, operation managers). This makes it difficult for the DT model to integrate full-lifecycle data, reducing the accuracy of sustainability simulation and optimization (Rossi et al., 2024). Additionally, there is a lack of mechanisms to share data between stakeholders, further exacerbating data silos.

5.3 Limited Accuracy of Sustainability-Oriented DT Models

Sustainability-oriented DT models need to simulate complex interactions between infrastructure, smart materials, and the environment across the full lifecycle. However, current models have limitations in simulating long-term material degradation, multi-factor environmental impacts (e.g., climate change, pollution), and circular economy processes (e.g., material recycling). For example, the simulation accuracy of material recycling rates during deconstruction is only 65-75%, affecting the reliability of sustainability evaluation (Patel et al., 2024). Additionally, the models often fail to fully consider social sustainability factors (e.g., infrastructure accessibility), leading to one-sided sustainability optimization.

5.4 Insufficient Awareness and Capacity of Stakeholders

Many infrastructure stakeholders (e.g., government departments, construction companies, operation managers) have insufficient awareness of the full-lifecycle sustainability benefits of SM-DT integration, focusing primarily on short-term economic costs. Additionally, there is a lack of professional capacity among stakeholders to apply SM-DT technology for sustainability management. For example, many construction companies lack engineers with expertise in both smart materials and digital twin technology, making it difficult to implement integration projects (Chen et al., 2024).

5.5 Regulatory and Policy Barriers

Current regulations and policies for urban infrastructure primarily focus on safety and performance, with limited consideration of full-lifecycle sustainability. There is a lack of mandatory sustainability evaluation standards and incentive policies for SM-DT integration. For example, no unified carbon emission accounting standards for infrastructure lifecycles exist in many regions, making it difficult to quantify the carbon reduction benefits of SM-DT integration. Additionally, the lack of policies supporting material recycling and circular economy hinders the implementation of deconstruction stage sustainability optimization (European Commission, 2024).

6. Strategies and Policy Recommendations

6.1 Technical Strategies

6.1.1 Develop Low-Cost, High-Performance Smart Materials

Increase R&D investment in low-cost, sustainable smart materials, such as recyclable self-healing polymers and low-cost PCMs, to reduce initial investment. For example, developing self-healing asphalt using industrial waste as raw materials can reduce material costs by 30-40% (Zhang et al., 2024). Additionally, improve the performance stability of smart materials to extend their service life and enhance sustainability benefits.

6.1.2 Improve DT Model Accuracy and Full-Lifecycle Integration Capability

Develop multi-physics, multi-scale DT models integrating long-term material degradation and environmental impact simulation. Integrate machine learning and AI technologies to improve model adaptability and prediction accuracy. Establish standardized data interfaces and integration mechanisms to realize full-lifecycle data sharing and integration between stakeholders (Gomez et al., 2024). Additionally, expand the model's scope to include social sustainability factors to achieve comprehensive sustainability optimization.

6.1.3 Promote Modular and Scalable Integration Solutions

Develop modular SM-DT integration solutions that can be tailored to different infrastructure types and sizes, reducing implementation complexity and costs. For example, develop standardized DT model modules for road, building, and water supply infrastructure, and matching smart material packages. This enables small and medium-sized infrastructure projects to adopt integration solutions at a lower cost (Patel et al., 2024).

6.2 Policy Recommendations

6.2.1 Establish Full-Lifecycle Sustainability Evaluation Standards

Governments and international organizations should formulate unified full-lifecycle sustainability evaluation standards for urban infrastructure, including indicators such as carbon emissions, resource utilization rate, and lifecycle cost. Incorporate these standards into infrastructure planning, design, and approval processes, making sustainability evaluation mandatory (European Commission, 2024). Additionally, establish standardized carbon emission accounting methods for infrastructure lifecycles to quantify the sustainability benefits of SM-DT integration.

6.2.2 Provide Financial Incentives and Support

Governments should provide financial incentives to promote SM-DT integration, such as subsidies for SM-DT integration projects (covering 20-30% of initial investment), tax breaks for sustainability benefits, and low-interest loans for long-term projects. Establish special funds to support R&D of low-cost smart materials and sustainability-oriented DT technologies. Encourage public-private partnerships (PPPs) to share investment risks and promote large-scale implementation (Li et al., 2024).

6.2.3 Strengthen Stakeholder Awareness and Capacity Building

Carry out training programs for government departments, construction companies, and operation managers to enhance their awareness of full-lifecycle sustainability and SM-DT integration technologies. Establish interdisciplinary education programs in universities and vocational colleges to train professionals with expertise in smart materials, digital twins, and infrastructure sustainability. Promote knowledge sharing through industry seminars and experience exchange platforms (Chen et al., 2024).

6.2.4 Formulate Policies Supporting Circular Economy and Material Recycling

Develop policies to promote infrastructure material recycling, such as mandatory recycling rates for construction materials, and incentives for using recycled smart materials. Establish a material tracking system based on DT technology to monitor the recycling process of infrastructure materials. Incorporate circular economy requirements into infrastructure deconstruction planning and approval processes (Zhang et al., 2024).

7. Conclusion

This study systematically explores the role of smart material and digital twin integration in advancing full-lifecycle sustainability of urban infrastructure, constructing a theoretical framework and analyzing integration paths for typical infrastructure types. The main findings are as follows: (1) The integration of SMs and DTs promotes full-lifecycle sustainability through three core synergistic mechanisms: data-driven lifecycle integration, simulation-based sustainability optimization, and circular economy promotion. (2) The full-lifecycle sustainability framework, covering design, construction, operation, maintenance, and deconstruction stages, provides a holistic management approach for urban infrastructure, with specific integration paths tailored to different infrastructure types. (3) Cross-regional case studies verify that SM-

DT integration significantly improves sustainability performance, including reducing carbon emissions by 35-45%, lowering lifecycle costs by 25-35%, and improving resource utilization rates by 50-85%. (4) The promotion of SM-DT integration for full-lifecycle sustainability faces challenges such as high initial investment, fragmented data standards, limited model accuracy, insufficient stakeholder capacity, and regulatory barriers. (5) Targeted technical strategies (developing low-cost SMs, improving DT models, promoting modular solutions) and policy recommendations (establishing evaluation standards, providing financial incentives, strengthening capacity building, supporting circular economy) can effectively address these challenges.

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