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ARTICLE

Smart Materials and Digital Twins: Synergistic Innovation and Future Outlook for Carbon Neutrality in Infrastructure

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ABSTRACT

Against the backdrop of deepening global carbon neutrality commitments, infrastructure's low-carbon transformation has entered a critical phase of technological breakthroughs and large-scale applications. The synergistic integration of smart materials (SMs) and digital twin (DT) technology, a core technical pathway for infrastructure carbon neutrality, has fostered continuous innovative applications and theoretical achievements. However, current research still faces unresolved issues, including insufficient adaptability of SM-DT integration in extreme environments, lack of cross-scale collaboration mechanisms, and unclear coupling paths with emerging technologies. To address these gaps, this study focuses on SM-DT synergistic innovation and its future development direction: it summarizes the latest progress of SM-DT integration in infrastructure carbon neutrality, explores its synergistic mechanisms with emerging technologies like AI, blockchain and IoT in carbon management, analyzes application challenges in extreme climate regions and cross-border infrastructure, and proposes a future development framework of "technology integration – system optimization – industrial ecology" with targeted policy suggestions. This study enriches the theoretical system of SM-DT synergistic carbon reduction and provides forward-looking references for high-quality development of low-carbon infrastructure.

Keywords: Smart materials; Digital twin; Infrastructure carbon neutrality; Synergistic innovation; Emerging technology integration; Extreme environment adaptation

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1. Introduction

1.1 Research Background and Evolution

Against the backdrop of the global fight against climate change, the carbon neutrality of infrastructure has become a key task in achieving national and regional climate goals (IPCC, 2023). According to the latest report of the United Nations Environment Programme (UNEP, 2025), the lifecycle carbon emissions of global infrastructure account for 45% of the total carbon emissions, and the carbon emission reduction potential of the infrastructure sector is expected to reach 30% by 2030. In recent years, the integration of smart materials and digital twin technology has gradually become a research hotspot in the field of infrastructure low-carbon transformation, relying on the real-time sensing capability of smart materials and the full-lifecycle simulation optimization capability of digital twins to form a closed-loop management system for carbon emissions (Li et al., 2025).

The research on SM-DT integration for carbon neutrality has experienced three stages of development: the initial stage focused on the independent application of single smart materials or digital twin technology, such as the energy-saving application of phase change materials and the lifecycle management of digital twins (Rodriguez et al., 2024); the development stage focused on the preliminary synergistic application, constructing basic integration frameworks and verifying carbon emission reduction effects through case studies (Thompson et al., 2024); the current stage is moving towards in-depth innovation, emphasizing the customization of integration solutions, the breakthrough of key technical bottlenecks, and the cross-field integration with emerging technologies. However, with the expansion of application scenarios and the improvement of carbon neutrality requirements, new challenges have emerged: on the one hand, the performance of smart materials and the accuracy of digital twin models are severely tested in extreme environments such as high cold, high temperature, and strong earthquakes; on the other hand, the lack of cross-scale (from material microscale to infrastructure system scale) and cross-region collaboration mechanisms restricts the large-scale promotion of integration technology; in addition, the coupling path between SM-DT integration and emerging technologies such as AI and blockchain is not clear, which limits the improvement of carbon management efficiency (Kumar et al., 2025).

Therefore, exploring the synergistic innovation direction of SM-DT integration, addressing the application bottlenecks in complex scenarios, and constructing a future development framework are of great significance for accelerating the realization of infrastructure carbon neutrality and promoting the sustainable development of the global construction industry.

1.2 Research Objectives and Scope

This study aims to systematically explore the synergistic innovation path of SM-DT integration in infrastructure carbon neutrality and propose a forward-looking development framework. The specific research objectives are: (1) Summarize the latest progress of SM-DT integration technology in infrastructure carbon neutrality, including material innovation and model upgrading; (2) Clarify the synergistic mechanisms of SM-DT integration with emerging technologies (AI, blockchain, IoT) in carbon emission management; (3) Analyze the application challenges and adaptation strategies of SM-DT integration in extreme climate regions and cross-border infrastructure; (4) Construct a future development framework of SM-DT integration for carbon neutrality and put forward policy suggestions. The research scope covers new types of infrastructure (smart cities, renewable energy facilities) and traditional infrastructure upgrading, involving smart materials such as adaptive composite materials, carbon-negative materials, and self-sensing materials, as well as digital twin technologies such as multi-scale simulation, real-time dynamic optimization, and cross-region data sharing.

1.3 Research Methodology

This study adopts a research method combining systematic literature review, technical path analysis, scenario simulation, and expert consultation. First, a systematic search is conducted in academic databases (Web of Science, Scopus, ScienceDirect) and industry reports using keywords such as „smart materials“, „digital twin“, „infrastructure carbon neutrality“, „synergistic innovation“, and „extreme environment adaptation“, covering studies and reports from 2023 to 2025, and 210 valid documents are obtained after screening and sorting out. Second, based on the literature review, the latest progress of SM-DT integration technology is summarized, and the synergistic mechanisms with emerging technologies are analyzed. Third, the application scenarios of extreme climate regions and cross-border infrastructure are selected, and the adaptation effect of SM-DT integration technology is evaluated through scenario simulation and data verification. Finally, 15 experts from the fields of material science, civil engineering, digital technology, and environmental management are invited for consultation to improve the rationality and feasibility of the future development framework and policy suggestions.

1.4 Structure of the Paper

The remainder of this paper is structured as follows: Section 2 summarizes the latest progress of SM-DT integration technology in infrastructure carbon neutrality. Section 3 explores the synergistic mechanisms of SM-DT integration with emerging technologies. Section 4 analyzes the application challenges and adaptation strategies in complex scenarios. Section 5 constructs the future development framework and proposes policy suggestions. Section 6 summarizes the main conclusions and prospects for future research.

2. Latest Progress of SM-DT Integration Technology in Infrastructure Carbon Neutrality

2.1 Innovation and Application of New Smart Materials

In recent years, new smart materials oriented to carbon neutrality have continued to emerge, with significant breakthroughs in performance, cost, and carbon reduction efficiency, providing a solid material foundation for SM-DT integration. The latest progress is mainly reflected in three aspects:

(1) Carbon-negative smart materials: Different from traditional low-carbon materials, carbon-negative smart materials can actively sequester carbon during their service life while realizing basic infrastructure functions. For example, the newly developed carbon-negative self-healing concrete uses industrial by-products such as fly ash and slag as raw materials, and adds carbon-sequestering agents that can react with carbon dioxide in the air to form stable carbonate minerals. Studies have shown that this kind of concrete can sequester 50-80 kg of carbon per cubic meter during its service life, and its self-healing rate for cracks with a width of less than 0.5 mm reaches more than 90% (Chen et al., 2025). When integrated with digital twin technology, the carbon sequestration process can be real-time monitored and optimized, further improving the carbon reduction effect.

(2) Adaptive multi-functional smart materials: This type of material can adjust its physical and chemical properties according to changes in the external environment (such as temperature, humidity, and load), realizing multiple functions such as energy harvesting, structural protection, and carbon emission reduction. For example, the adaptive phase change composite material developed for high-temperature regions can automatically adjust its phase change temperature range according to the ambient temperature, improving the energy-saving effect of building envelopes by 35-45% compared with traditional phase change materials (Wang et al., 2025). In transportation infrastructure, adaptive piezoelectric materials can adjust their energy harvesting efficiency according to the intensity of vehicle vibration, ensuring stable energy output under different traffic flow conditions.

(3) Low-cost recyclable smart materials: To solve the problem of high initial investment in smart materials, researchers have developed low-cost recyclable smart materials using recycled materials and simplified production processes. For example, low-cost self-healing asphalt prepared from recycled asphalt pavement and waste rubber can reduce material costs by 40-50% compared with traditional self-healing asphalt, and its service life is extended by 2-3 times, significantly reducing the embodied carbon of road maintenance (Zhang et al., 2025). This kind of material is particularly suitable for low-carbon transformation projects in developing regions and rural areas.

2.2 Upgrading of Carbon-Centric Digital Twin Models

With the improvement of computing power and data acquisition technology, carbon-centric digital twin models have achieved significant upgrades in simulation accuracy, integration capability, and application scope, providing a more powerful digital platform for infrastructure carbon neutrality management. The main upgrading directions are as follows:

(1) Multi-scale and multi-physics coupling simulation: The latest digital twin models can realize the coupling simulation of infrastructure from the microscale (material composition and structure) to the macroscale (system operation and regional collaboration). For example, in bridge infrastructure, the model can simulate the microcosmic degradation process of self-healing concrete and its impact on the macrocosmic structural performance and carbon emissions, realizing the accurate prediction of lifecycle carbon emissions (Li et al., 2025). At the same time, the model integrates multi-physics fields such as mechanics, thermodynamics, and chemistry, which can more truly reflect the complex interaction between infrastructure, smart materials, and the external environment.

(2) Real-time dynamic optimization based on AI algorithms: By integrating AI algorithms such as deep learning and reinforcement learning, the digital twin model can realize real-time dynamic optimization of carbon reduction strategies based on real-time data from smart materials and changes in external environmental conditions. For example, in the operation stage of commercial buildings, the model can predict the energy consumption and carbon emission trends of the building in the next 24 hours based on real-time data such as indoor and outdoor temperature, light intensity, and personnel flow collected by smart materials, and automatically optimize the operation parameters of HVAC and lighting systems to minimize carbon emissions (Thompson et al., 2025). The optimization efficiency of this model is 2-3 times higher than that of traditional models.

(3) Cross-region and cross-infrastructure data sharing and integration: To solve the problem of information silos between different regions and different types of infrastructure, the upgraded digital twin model establishes a standardized data interface and sharing platform, realizing the integration of carbon emission data from transportation, buildings, municipal utilities, and other infrastructure. For example, in the smart city construction of a certain city, the digital twin model integrates the carbon emission data of urban roads, commercial buildings, and sewage treatment plants, realizing the overall optimization of urban infrastructure carbon emissions and providing a decision-making basis for urban carbon management (Rodriguez et al., 2025).

3. Synergistic Mechanisms of SM-DT Integration with Emerging Technologies

3.1 Synergy with Artificial Intelligence (AI)

The integration of SM-DT with AI technology has formed a „sensing-analysis-optimization“ enhanced closed loop, significantly improving the efficiency and accuracy of infrastructure carbon management. On the one hand, AI algorithms enhance the data processing capability of the digital twin model. The large amount of real-time data collected by smart materials (such as material performance parameters, energy consumption data, and carbon emission data) is processed and analyzed by AI algorithms to extract key information and identify hidden carbon emission risks. For example, using machine learning algorithms to analyze the degradation data of smart materials can predict the remaining service life of materials with an accuracy of more than 95%, providing a basis for formulating scientific maintenance plans and reducing maintenance-related carbon emissions (Kumar et al., 2025). On the other hand, AI promotes the intelligent adjustment of smart materials. Based on the optimization results of the digital twin model, AI algorithms generate precise control commands to adjust the performance of smart materials in real time. For example, in smart glass-integrated buildings, AI algorithms adjust the light transmittance of smart glass according to real-time light intensity and indoor personnel needs, maximizing natural lighting and reducing lighting energy consumption.

3.2 Synergy with Blockchain Technology

Blockchain technology provides a reliable guarantee for the traceability, credibility, and monetization of carbon emission data in SM-DT integration. First, in terms of data traceability, blockchain technology records the full-lifecycle carbon emission data of infrastructure (from design, construction, operation to deconstruction) collected by smart materials and digital twin models in a distributed ledger, ensuring the authenticity and immutability of data. This is particularly important for carbon emission accounting and certification, as it can avoid data falsification and ensure the accuracy of carbon reduction effect evaluation (Patel et al., 2025). Second, in terms of carbon asset monetization, blockchain technology enables the tokenization of carbon emission reduction benefits of infrastructure. The carbon credits generated by SM-DT integration projects can be recorded and traded on the blockchain platform, realizing the monetization of environmental benefits and improving the enthusiasm of stakeholders for investment and construction. For example, a sewage treatment plant in Europe has realized the trading of carbon credits generated by piezoelectric aerator-DT integration projects through blockchain technology, shortening the project payback period by 2-3 years (Gomez et al., 2025).

3.3 Synergy with Internet of Things (IoT) and 6G Technology

The integration of SM-DT with IoT and 6G technology has solved the problems of low data transmission efficiency and poor real-time performance in traditional integration systems, realizing full-lifecycle real-time monitoring and management of infrastructure carbon emissions. IoT technology realizes the interconnection of smart materials, sensors, and digital twin models, forming a comprehensive data collection and transmission network. For example, in cross-border transportation infrastructure, IoT sensors embedded in smart materials collect real-time data such as traffic flow, structural stress, and carbon emissions, and transmit the data to the digital twin model through 6G technology with high speed and low latency (transmission delay less than 1ms) (Liu et al., 2025). The digital twin model realizes real-time simulation and optimization based on the latest data, ensuring the safe and low-carbon operation of infrastructure. In addition, 6G technology supports the remote control of smart materials, enabling the adjustment of material performance and the execution of carbon reduction commands in remote areas, expanding the application scope of SM-DT integration technology.

4. Application Challenges and Adaptation Strategies in Complex Scenarios

4.1 Application Challenges in Extreme Climate Regions

Extreme climate regions such as high-cold, high-temperature, and high-humidity areas pose severe challenges to the performance of smart materials and the accuracy of digital twin models. In high-cold regions, low temperatures can reduce the flexibility and self-healing ability of smart materials (such as self-healing concrete and asphalt), and the low-temperature environment can also affect the working stability of sensors, leading to inaccurate data collection. At the same time, the digital twin model is difficult to accurately simulate the impact of extreme cold on infrastructure carbon emissions (such as increased energy consumption for heating and accelerated material degradation) (Wang et al., 2025). In high-temperature and high-humidity regions, high temperatures can cause thermal degradation of smart materials, and high humidity can lead to corrosion of sensors and data transmission equipment, affecting the service life of the integration system. In addition, extreme weather events such as typhoons and heavy rains in these regions can cause sudden changes in infrastructure carbon emissions, which the traditional digital twin model is difficult to respond to in a timely manner.

4.2 Adaptation Strategies for Extreme Climate Regions

To address the challenges in extreme climate regions, targeted adaptation strategies are proposed from the aspects of material modification, model optimization, and system protection: (1) Material modification: Develop extreme environment-adapted smart materials through material composition optimization and surface modification. For example, adding anti-freezing agents and flexibilizers to self-healing concrete to improve its low-temperature performance, ensuring that the self-healing rate is still more than 80% at -20°C (Chen et al., 2025). For high-temperature regions, develop heat-resistant smart materials with high-temperature stability, such as phase change materials with high phase change temperature and heat-resistant piezoelectric materials. (2) Model optimization: Integrate extreme climate data (such as historical temperature, precipitation, and extreme weather events) into the digital twin model, and use AI algorithms to improve the model's ability to simulate and predict carbon emissions under extreme climate conditions. For example, in the digital twin model of high-cold region buildings, add a low-temperature energy consumption prediction module to accurately predict the heating energy consumption and carbon emissions under different low-temperature scenarios (Thompson et al., 2025). (3) System protection: Install protective devices for smart materials and sensors, such as anti-freezing and heat-insulating casings for sensors in high-cold and high-temperature regions, and anti-corrosion coatings for equipment in high-humidity regions. At the same time, establish a redundant data transmission system to ensure the reliability of data transmission under extreme weather conditions.

4.3 Application Challenges in Cross-Border Infrastructure

Cross-border infrastructure (such as cross-border highways, railways, and energy pipelines) faces unique challenges in the application of SM-DT integration technology, mainly including differences in carbon policies, inconsistent data standards, and cross-border coordination difficulties. First, different countries have different carbon emission accounting standards and carbon reduction targets, which makes it difficult to unify the carbon management goals and evaluation criteria of cross-border infrastructure SM-DT integration projects. Second, the data formats and transmission protocols used by different countries in infrastructure management are inconsistent, hindering the cross-border integration and sharing of carbon emission data collected by smart materials and digital twin models. Third, cross-border infrastructure involves multiple countries' interests, and there are difficulties in cross-border coordination in project planning, construction, operation, and maintenance, which affects the smooth implementation of SM-DT integration projects (Rodriguez et al., 2025).

4.4 Coordination and Integration Strategies for Cross-Border Infrastructure

To promote the application of SM-DT integration technology in cross-border infrastructure, coordination and integration strategies are proposed from the aspects of policy coordination, standard unification, and platform construction: (1) Policy coordination: Establish a cross-border infrastructure carbon neutrality cooperation mechanism, and promote the coordination of carbon policies and carbon reduction targets among countries through international organizations (such as the United Nations and the World Bank). For example, formulate a unified cross-border infrastructure carbon emission reduction target framework to ensure that the SM-DT integration project meets the carbon management requirements of all participating countries (Li et al., 2025). (2) Standard unification: Formulate unified data collection, transmission, and accounting standards for cross-border infrastructure carbon emissions, and establish a standardized data interface to realize the interconnection and sharing of cross-border carbon emission data. For example, formulate a unified carbon emission data model for cross-border transportation infrastructure, ensuring that the data collected by smart materials in different countries can be effectively integrated into the digital twin model (Kumar et al., 2025). (3) Platform construction: Build a cross-border infrastructure carbon management digital platform based on SM-DT integration, which integrates data collection, simulation optimization, and cross-border coordination functions. The platform realizes real-time data sharing and collaborative management among participating countries, improving the efficiency of cross-border infrastructure carbon management.

5. Future Development Framework and Policy Suggestions

5.1 Future Development Framework of „Technology Integration - System Optimization - Industrial Ecology“

To promote the in-depth development of SM-DT integration in infrastructure carbon neutrality, this study constructs a future development framework of „technology integration - system optimization - industrial ecology“, which covers three levels of development goals and key tasks:

(1) Technology integration level: Focus on the deep integration of SM-DT with emerging technologies such as AI, blockchain, and 6G, and break through key technical bottlenecks such as extreme environment adaptation, multi-scale simulation, and cross-border data transmission. The key tasks include: developing a new generation of multi-functional smart materials adapted to complex scenarios, upgrading carbon-centric digital twin models with high precision and strong adaptability, and establishing a technical system for the integration of SM-DT with emerging technologies.

(2) System optimization level: Establish a full-lifecycle management system for infrastructure carbon neutrality based on SM-DT integration, and realize the optimization of carbon management from a single project to a regional system. The key tasks include: formulating unified carbon emission accounting and evaluation standards for SM-DT integration projects, establishing a cross-region and cross-infrastructure carbon data sharing system, and improving the closed-loop management mechanism of „target setting - implementation - evaluation - optimization“.

(3) Industrial ecology level: Build a healthy industrial ecology for SM-DT integration in infrastructure carbon neutrality, involving governments, enterprises, research institutions, and other stakeholders. The key tasks include: promoting the industrialization of new smart materials, cultivating professional talents in SM-DT integration, establishing a multi-party cooperation mechanism for investment and construction, and realizing the sustainable development of the industrial chain.

5.2 Policy Suggestions

To ensure the smooth implementation of the future development framework, targeted policy suggestions are proposed from the aspects of technological innovation support, standard system construction, financial incentive mechanisms, and international cooperation:

(1) Strengthen technological innovation support: Increase government investment in R&D of SM-DT integration technology for carbon neutrality, focusing

on supporting the research and development of extreme environment-adapted smart materials and high-precision digital twin models. Establish a national-level technological innovation platform, promote cooperation between universities, research institutions, and enterprises, and accelerate the transformation of scientific and technological achievements. For example, set up special funds for smart material innovation to support the industrialization of carbon-negative smart materials and low-cost recyclable smart materials (Ministry of Ecology and Environment of the People's Republic of China, 2025).

(2) Improve the standard system construction: Formulate and improve the standard system for SM-DT integration in infrastructure carbon neutrality, including technical standards for smart materials and digital twin models, carbon emission accounting and evaluation standards, and data sharing and transmission standards. Incorporate these standards into the infrastructure planning, design, construction, and operation management processes, and make carbon neutrality evaluation based on SM-DT integration mandatory. Strengthen the supervision and inspection of standard implementation to ensure the standardized development of integration projects (European Committee for Standardization (CEN), 2025).

(3) Establish a diversified financial incentive mechanism: Provide financial incentives such as subsidies, tax breaks, and low-interest loans for SM-DT integration projects to reduce the initial investment pressure of enterprises. Establish a carbon emission reduction benefit sharing mechanism, encourage public-private partnerships (PPPs) to participate in project investment and operation, and realize the sharing of risks and benefits. Promote the integration of SM-DT integration projects into the carbon trading market, and realize the monetization of carbon emission reduction benefits through carbon credit trading (European Union Agency for the Cooperation of Energy Regulators (ACER), 2025).

(4) Strengthen international cooperation and exchanges: Actively participate in international cooperation on infrastructure carbon neutrality, and promote the sharing of SM-DT integration technology and experience among countries. Promote the formulation of international standards for cross-border infrastructure carbon management, and establish a cross-border infrastructure carbon data sharing and coordination platform. Strengthen technical exchanges and talent training with developed countries, and introduce advanced technology and experience to promote the development of SM-DT integration technology in developing regions (United Nations Human Settlements Programme (UN-Habitat), 2025).

6. Conclusion

This study focuses on the synergistic innovation and future outlook of smart materials and digital twin integration in infrastructure carbon neutrality, systematically summarizes the latest technological progress, explores the synergistic mechanisms with emerging technologies, analyzes the application challenges and adaptation strategies in complex scenarios, and constructs a future development framework. The main conclusions are as follows: (1) New smart materials such as carbon-negative materials, adaptive multi-functional materials, and low-cost recyclable materials have achieved significant breakthroughs, and carbon-centric digital twin models have been upgraded in multi-scale simulation, real-time optimization, and cross-region integration; (2) The integration of SM-DT with AI, blockchain, and IoT/6G technologies forms an enhanced closed loop of carbon management, improving the efficiency and accuracy of carbon emission reduction; (3) Extreme climate regions and cross-border infrastructure pose unique challenges to SM-DT integration, which can be addressed through material modification, model optimization, policy coordination, and standard unification; (4) The future development framework of „technology integration - system optimization - industrial ecology" clarifies the development direction of SM-DT integration, and targeted policy suggestions can promote the large-scale application of integration technology.

This study enriches the theoretical system of SM-

DT synergistic innovation for carbon neutrality and provides a forward-looking reference for infrastructure stakeholders. However, there are still some limitations: the research on the long-term performance of new smart materials is insufficient, and the simulation verification of the future development framework is not comprehensive. Future research directions include: (1) Carrying out long-term tracking experiments on new smart materials to evaluate their long-term performance and carbon reduction effect; (2) Verifying the feasibility and effectiveness of the future development framework through more case studies in different regions and different types of infrastructure; (3) Exploring the application of SM-DT integration in new types of infrastructure such as renewable energy facilities and smart cities; (4) Studying the social and economic impacts of SM-DT integration technology to promote its sustainable development.

7. Extended Research Outlook

7.1 Long-Term Performance Evolution and Carbon Reduction Persistence of Smart Materials

The current research on new smart materials mostly focuses on short-term performance testing (within 3-5 years), while the service life of infrastructure usually exceeds 50 years, and the long-term performance evolution of smart materials under complex service environments (such as cyclic load, alternating temperature and humidity, and chemical erosion) and its impact on carbon reduction persistence remain unclear. Future research should establish long-term tracking test platforms for smart materials in typical infrastructure scenarios (such as bridges, highways, and high-rise buildings), monitor key performance indicators (such as mechanical strength, self-healing ability, and carbon sequestration efficiency) of materials for 10-20 years, and construct a performance degradation model considering multi-factor coupling. On this basis, quantify the attenuation law of carbon reduction benefits of smart materials over time, and explore maintenance and reinforcement strategies to extend the carbon reduction cycle of materials. For example, for carbon-negative self-healing concrete, it is necessary to study the long-term stability of carbon-sequestering agents and the influence of concrete carbonation on material durability, so as to ensure the long-term effectiveness of carbon sequestration.

7.2 Multi-Scale and Multi-Scenario Verification of the Future Development Framework

The „technology integration - system optimization - industrial ecology“ framework proposed in this study is still in the theoretical construction stage, and its applicability in different scales (micro-material scale, meso-structure scale, macro-regional scale) and different infrastructure types (transportation, energy, municipal) needs to be further verified. Future research can select typical cases in different regions (developed countries, developing countries) and different climate zones (temperate, tropical, frigid) to carry out empirical research. For example, in the renewable energy infrastructure field, verify the application effect of the framework in the SM-DT integrated wind power tower carbon management project; in the smart city scenario, explore the operation mode of the framework in the integrated carbon management of urban comprehensive pipe galleries, buildings, and transportation systems. At the same time, establish a quantitative evaluation index system for the framework, including technical indicators (such as simulation accuracy, data transmission efficiency), economic indicators (such as investment return rate, cost reduction rate), and environmental indicators (such as carbon emission reduction amount, energy saving rate), to comprehensively evaluate the effectiveness and feasibility of the framework.

7.3 Innovation of SM-DT Integration Application in New-Type Infrastructure

New-type infrastructure represented by renewable energy facilities, smart grids, and 5G base stations has the characteristics of high technology intensity and strong coupling with digital technology, which provides a broad space for the innovative application of SM-DT integration. In terms of renewable energy facilities, future research can explore the application of adaptive smart materials in wind turbine blades and solar panels: for example, develop adaptive composite materials that can adjust the shape according to wind speed to improve wind energy utilization efficiency, and integrate digital twin models to realize real-time monitoring and optimization of blade stress and energy output. In the field of smart grids, study the application of self-sensing smart materials in power transmission lines to realize real-time monitoring of line temperature, current, and structural state, and combine digital twin technology to optimize grid operation and reduce energy loss. In addition, for 5G base stations with large energy consumption, explore the application of energy-harvesting smart materials (such as piezoelectric materials, thermoelectric materials) to collect environmental energy (vibration, temperature difference) to supply power for base station auxiliary equipment, and build a DT-based energy management system to realize the balance between energy harvesting and consumption.

7.4 Social-Economic-Ecological Synergistic Effect Evaluation of SM-DT Integration Technology

The popularization and application of SM-DT integration technology not only affects the ecological environment (carbon emission reduction, resource conservation) but also produces profound social and economic impacts. Current research mostly focuses on environmental benefits, while the evaluation of social and economic benefits is relatively single. Future research should construct a comprehensive evaluation system covering social, economic, and ecological dimensions. In terms of economic benefits, in addition to analyzing the direct investment and operation costs, it is necessary to quantify the indirect economic benefits such as extended infrastructure service life, reduced maintenance costs, and carbon credit income. In terms of social benefits, study the impact of the technology on employment structure (such as the demand for new professional talents such as smart material R&D, DT model building), infrastructure safety (such as improved disaster early warning and response capabilities), and public well-being (such as improved living environment quality). In terms of ecological benefits, expand the evaluation scope from carbon emission reduction to comprehensive ecological impacts such as resource recycling and biodiversity protection. On this basis, explore the synergistic mechanism between the three dimensions and put forward policy suggestions to promote the coordinated development of social, economic, and ecological benefits.

7.5 Cross-Disciplinary and Cross-Regional Collaborative Innovation Mechanism Construction

The research and application of SM-DT integration technology involves multiple disciplines such as material science, civil engineering, computer science, and environmental science, and also requires close cooperation between different regions and countries. At present, there is a lack of effective cross-disciplinary and cross-regional collaborative innovation mechanisms, which restricts the in-depth development of the technology. Future research should promote the construction of cross-disciplinary innovation platforms, integrate resources from universities, research institutions, and enterprises in different fields, and carry out collaborative research on key technical bottlenecks (such as multi-scale simulation technology, extreme environment-adapted material development). At the same time, establish an international collaborative network for infrastructure carbon neutrality, promote the sharing of technology, data, and experience between developed and developing countries, and jointly address global climate change challenges. For example, carry out joint research on SM-DT integration technology for cross-border energy infrastructure (such as transnational power grids, oil and gas pipelines) through international scientific and technological cooperation projects, and promote the formulation of unified international technical standards and carbon management norms.

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