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Transforming construction: digital twin technology for site monitoring and optimization in Denmark

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Abstract: Digital twin (DT) technology is revolutionizing the construction industry by creating real-time digital replicas of physical assets, enabling enhanced monitoring, optimization, and decision-making. In Denmark, the integration of DTs aligns with national objectives for sustainability and digital innovation, supported by collaborative efforts among research institutions, government, and industry stakeholders. Despite significant progress, several challenges persist, including integrating diverse data sources, ensuring cybersecurity, and managing implementation costs. Addressing these barriers is critical to scaling DT adoption and maximizing its potential in construction applications. This paper anticipates significant advancements, such as AI-driven predictive analytics, integration with circular economy practices, and the establishment of open standards to ensure seamless interoperability. The findings demonstrate how Denmark's DT initiatives are reshaping the construction landscape, offering practical insights into overcoming barriers and advancing sustainability goals. In conclusion, Denmark's proactive adoption of DT technology serves as a blueprint for leveraging innovation to create smarter, more sustainable construction practices, setting a benchmark for global efforts in this domain.

Keywords: digital twins; site monitoring and optimization; construction industry; real-time data integration; sustainability in construction; IoT and AI in buildings; digitalization of infrastructure; Denmark's digital twin initiatives

1. Introduction

Digital twin (DT) technology is transforming industries by creating digital replicas of physical assets that harness real-time data to enhance performance and inform decision-making [1]. Figure 1 provides a diagram of a building digital twin with its main components and connections. In the construction sector, DTs are revolutionizing project monitoring and optimization, reducing costs, increasing safety, and promoting sustainability. In Denmark, DT technology is at the heart of ongoing digitalization and sustainable urban development initiatives, including the Denmark Green Transition strategy and Industry 4.0 advancements, aligning closely with national goals for environmental and economic sustainability.

Building Information Modeling (BIM) stands as a cornerstone of the building sector's digital transformation, marking one of the most significant technological advancements in the construction industry [2]. At its core, BIM is a comprehensive digital representation of a building or infrastructure, encapsulating both its functional and physical attributes. It is more than a tool; it is a structured framework of processes, technologies, and guidelines that enable stakeholders to collaboratively plan, design, construct, and manage buildings and facilities in a virtual environment. Over the years, BIM concepts and applications have evolved significantly, introducing various levels of sophistication, with 6D BIM serves as a foundation for facilities maintenance and lifecycle management. These advancements have propelled BIM into a vital role, offering tangible benefits during design and construction phases. These include more accurate facility designs, improved project oversight, reduced costs, shortened timelines, and enhanced collaboration among diverse project teams.

Despite these advantages, current BIM practices often fall short of their full potential. BIM is frequently limited to meeting basic requirements during construction and is then sidelined once the project is complete, offering little value for ongoing facility management or operational optimization. A promising development lies in the integration of BIM with IoT-based data sources [3]. This synergy brings together the strengths of both technologies to overcome their individual limitations. BIM models provide detailed, high-fidelity representations of a project at the component level, while IoT data offers near-real-time operational insights and performance metrics. By combining these perspectives, stakeholders can achieve a more dynamic and comprehensive understanding of a building's lifecycle, from design through operation, paving the way for smarter, more sustainable infrastructure management.

This article examines how DT technology is currently being used to optimize construction sites across Denmark and explores anticipated future trends. It reviews the current state of DT technology, key industry initiatives, challenges, future directions, and real-life case studies, showcasing Denmark's proactive stance on integrating digital twins into construction.

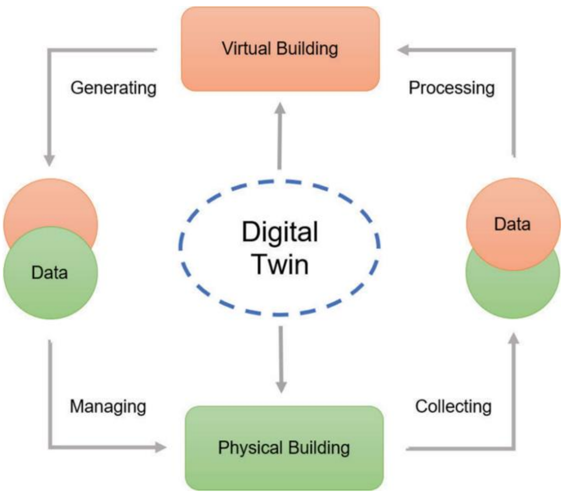

Figure 1. Digital twin concept.

2. Overview of digital twin technology in construction

2.1. Definition and features

Digital twins are virtual counterparts of physical assets, whether buildings, systems, or infrastructure, that mirror real-time conditions and simulate potential scenarios. For instance, Figure 2 presents the DT concept with typical systems and components present in buildings along with their virtual counterpart and the bidirectional flow of data [4]. Developed through a blend of data from IoT sensors, Building Information Modeling (BIM), artificial intelligence, and machine learning algorithms, DTs in construction create precise digital replicas that continuously adapt as conditions change [5]. Key components that make DTs effective in construction include:

- IoT and Sensor Integration: IoT devices capture on-site data like temperature, humidity, vibration, and worker movement, providing a steady stream of information that feeds into the digital model.
- BIM Integration: BIM acts as the blueprint within the DT, forming the structural framework and visualizing progress overlaid with real-time data.
- Analytics and Simulation: AI and ML algorithms analyze incoming data for predictive insights and risk analysis, making DTs not only descriptive but also prescriptive.
- Cloud and Edge Computing: These provide the necessary computing power for processing and storing data. Edge computing can process data close to the source for faster decisions, while cloud computing offers extensive storage and processing capabilities.

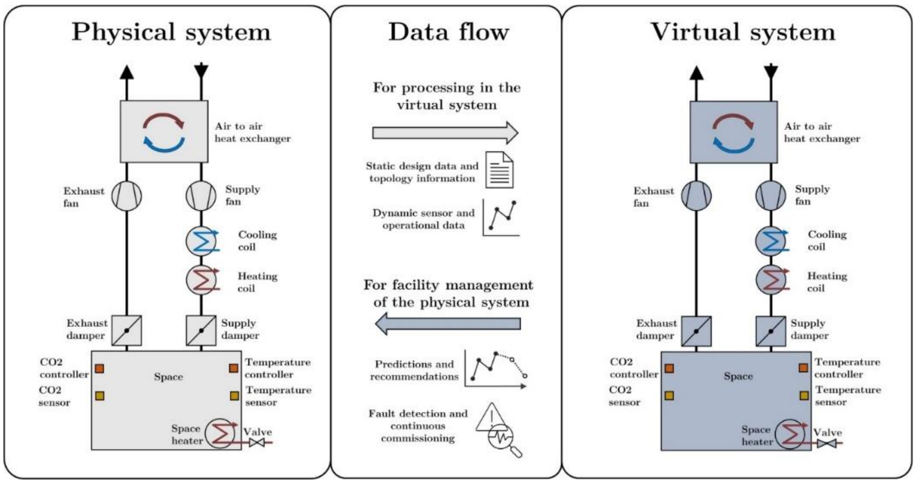

Figure 2. A building digital twin with various systems and components along with data interactions [4].

2.2. Applications in construction

Digital twins in construction sites enhance many operational and management aspects, including [6,7]:

- Safety Monitoring: DTs detect and monitor potential hazards by analyzing worker activity, equipment status, and environmental conditions, significantly reducing on-site accidents.
- Progress Tracking and Forecasting: DTs track the construction process in real time, helping project managers visualize timelines and adjust resources as needed.
- Resource and Inventory Management: By analyzing material usage and availability, DTs help reduce waste and improve sustainability in resource utilization.
- Environmental Monitoring: DTs measure emissions, energy consumption, and other environmental metrics to assess and mitigate the project's environmental impact.
- Quality Assurance and Defect Management: DTs provide a historical record and ongoing analysis that help identify quality issues, facilitating faster corrections and preventing larger issues.

2.3. Benefits of digital twins

The benefits of DTs in construction sites include:

- Enhanced Decision Support: Real-time insights aid managers in making better decisions on resource allocation, scheduling, and safety protocols.
- Predictive Maintenance and Risk Prevention: By analyzing equipment wear and usage patterns, DTs can schedule preventive maintenance and avoid unexpected equipment failures.
- Sustainability and Waste Reduction: DTs optimize resource management to reduce waste and energy use, contributing to sustainability goals.
- Improved Stakeholder Communication: Real-time digital models provide a shared platform for all stakeholders, improving transparency and collaboration.

3. Current state of digital twins in Denmark's construction industry

Denmark has become a frontrunner in adopting digital twin technology within the construction industry, propelled by innovative research, strong government backing, and close industry collaboration. The integration of DTs aligns seamlessly with Denmark's national goals for sustainability and digitalization, prioritizing energy efficiency, carbon reduction, and the adoption of advanced digital technologies. This section explores the current landscape of DT adoption in Denmark's construction sector, spotlighting pioneering research and development projects, government initiatives, and key industry leaders driving this transformation.

3.1. Research and industry initiatives

A range of research and industry initiatives are propelling digital twin technology forward in Denmark's construction sector. These projects are largely collaborative, uniting academic institutions, industry leaders, and government bodies to unlock the potential of DTs in areas like construction site monitoring, project optimization, and sustainable building operations.

Led by the University of Southern Denmark (SDU), Twin4Build is a pioneering project focused on using digital twins to enhance energy management, climate control, and operational efficiency in building environments. The project aims to establish a standardized DT framework that seamlessly integrates Building Information Modeling (BIM), IoT, and AI-driven analytics to monitor and optimize energy use and indoor climate in real time, as illustrated in Figure 3. Twin4Build is a major initiative in Denmark's construction sector, showcasing the potential of DTs to lower energy consumption, improve occupant comfort, and provide facility managers with actionable insights. Through collaboration with industry and public institutions, Twin4Build models a scalable approach for DT adoption in Denmark, prioritizing interoperability, data standardization, and practical scalability.

Figure 3. Twin4Build digital twin platform framework.

Energy Cluster Denmark [8], a national innovation hub, plays a pivotal role in driving the advancement of digital twin technology within Denmark's construction sector. The organization facilitates collaborative projects between energy companies, construction firms, and research institutions, with a focus on integrating DTs into energy management solutions. Through its initiatives, Energy Cluster Denmark actively promotes the adoption of DTs, showcasing their ability to enhance energy efficiency and operational performance in both new and existing buildings.

Beyond academic-led initiatives, private sector partnerships are significantly advancing digital twin applications in construction. Notable collaborations, such as those between COWI, KMD, and other technology and consulting firms, exemplify this progress. For instance, COWI has utilized DTs in infrastructure projects to monitor construction progress, optimize material usage, and strengthen safety protocols. These partnerships highlight the Danish construction industry's commitment to making DTs a core component of its digital transformation strategy, leveraging expertise from both public and private sectors to fuel innovation and enhance project outcomes.

3.2. Government and policy support

The Danish government has been a key enabler of DT adoption in construction through policies, funding programs, and regulatory frameworks aimed at advancing digitalization and sustainability. Noteworthy government initiatives that support DT adoption in the construction industry include:

(1) The green digital transition

Denmark's Green Digital Transition initiative promotes digital solutions that drive energy savings, resource efficiency, and carbon reduction across multiple industries, with a strong emphasis on construction [9]. Digital twins are a key focus within this program, receiving financial support and technical guidance to help implement sustainable practices. Through funding pilot projects and encouraging research into DT applications, the Danish government aims to accelerate DT adoption, advancing the construction sector toward greater energy efficiency and a low-carbon future.

(2) The Danish energy agency's energy labelling scheme

The Danish Energy Agency has launched an Energy Labelling Scheme focused on improving energy performance in buildings, with digital twins emerging as vital tools for meeting and verifying these efficiency targets [10]. Through this scheme, construction companies and building operators can use DTs to monitor energy consumption, forecast savings, and support Denmark's ambitious climate goals. The agency also promotes DT-enabled retrofitting and ongoing energy monitoring to optimize efficiency in both new and existing buildings, reinforcing Denmark's commitment to sustainable energy use in the construction sector.

(3) Strategic partnerships with EU programs

Denmark participates in several EU-level digital and green transition initiatives, such as Horizon Europe and Digital Europe, which provide funding and resources for DT research and implementation. Denmark's involvement in these programs supports collaboration with other EU countries and facilitates knowledge-sharing on DT technologies and best practices, enhancing the capacity of Danish construction companies to adopt cutting-edge DT solutions.

(4) Public procurement and digital standards

The Danish government has also developed public procurement guidelines that encourage the use of DTs in publicly funded construction projects. These guidelines prioritize digital solutions that promote efficiency, transparency, and sustainability, and DT technology is often a requirement for projects that involve infrastructure development and urban planning. This policy approach not only promotes the adoption of DTs but also ensures that DT-enabled projects align with national digital and environmental standards.

3.3. Key players in the Danish digital twin ecosystem

The success of digital twins in Denmark's construction industry is largely attributed to collaborative efforts among key players with expertise in technology, construction, and research. These stakeholders include:

- IT and Software Firms: Leading Danish IT and software companies play a pivotal role in advancing digital twin technology for infrastructure and facility management. Collaborating with public institutions and construction companies, these firms provide customized DT solutions that enhance building operations, improve safety, and align with sustainability goals. Their partnerships reflect a commitment to using DTs for real-time monitoring, predictive maintenance, and boosting energy efficiency across construction projects.
- Engineering and Consulting Companies: Renowned Danish engineering and consulting firms leverage DTs in complex infrastructure projects, including major transportation links and urban developments. They apply DT expertise in areas like safety management, resource optimization, and environmental impact tracking, showcasing DTs' value in large-scale, high-stakes projects. Their work highlights how DTs enhance project quality and sustainability through proactive management and risk minimization.
- Danish Technological Institute (DTI): The Danish Technological Institute is deeply involved in DT research, focusing on establishing industry standards, exploring innovative applications, and advancing interoperability frameworks. By partnering with both public and private sectors, DTI bridges research with real-world construction applications. DTI's work on best practices and standards contributes to a more unified and interoperable DT ecosystem in Denmark.
- Energy Cluster Denmark: This national innovation cluster fosters collaborative projects that integrate DTs with energy-efficient solutions. Energy Cluster Denmark connects energy companies with construction firms to deploy DTs that promote efficient resource use, optimize energy consumption, and support Denmark's climate goals. The cluster also identifies new business opportunities for DT applications, such as lifecycle management and sustainability metrics.
- Danish Universities: Universities like DTU and SDU are central to DT research and education, conducting groundbreaking studies on DT applications for smart buildings, resource management, and lifecycle analysis. Through these research programs, they

not only advance DT technology but also train the next generation of engineers and data scientists, strengthening Denmark's evolving digital construction sector.

3.4. Integration across the construction sector

In Denmark, digital twin technology is no longer confined to isolated projects or pilot programs; it is becoming an integral part of the construction industry's digital strategy. DTs are being embedded across multiple phases of the building lifecycle, from planning and design to construction and facility management. Denmark's focus on developing open, interoperable DT platforms, often based on standards like NGSI-LD and SAREF [4], ensures these digital tools are accessible, scalable, and adaptable for diverse applications.

Construction firms in Denmark are increasingly using DTs to engage stakeholders, boost transparency, and support collaborative decision-making. By offering a real-time digital representation of construction sites and ongoing projects, DTs improve communication among contractors, architects, engineers, and clients, resulting in more efficient project delivery and enhanced project outcomes.

4. A hospital building DT case

As part of the Twin4Build project, a highly adaptable and flexible digital twin platform was developed using an ontology-based, data-driven energy modeling framework. This platform was tested in a real-world case study involving a two-story hospital building. The facility features a dedicated ventilation system with a capacity of approximately 10,000 m^3/h, a rotating heat exchanger, and water coils for heating and cooling. The building is connected to a district heating system, where the supply water temperature varies between 50 °C and 60 °C, depending on outdoor conditions.

A key component of the study was the development of a semantic model to serve as a machine-readable representation of the building's physical systems. This semantic model encapsulated details such as system topology, component interrelationships, and equipment specifications. By integrating this semantic model with simulation tools, the digital twin demonstrated how real-time updates could dynamically impact simulation predictions, providing a robust decision-making framework for performance optimization.

During the commissioning phase, the digital twin identified a critical design flaw: an undersized space heater in one area of the building. This heater consistently operated with its valve fully open but was unable to maintain the desired room temperature setpoint. Using the platform, several optimization scenarios were evaluated to resolve this issue:

- Increased Supply Water Temperature: By raising the supply water temperature, heating setpoint violations were reduced by 18%.
- Supplementary Heater Installation: Adding a supplementary heater addressed the undersized capacity, decreasing thermal comfort violations by 73%.
- Combined Solution: Implementing a 430W supplementary heater alongside an increased supply water temperature achieved an 84% reduction in thermal discomfort, significantly enhancing overall comfort compared to the baseline scenario.

These findings illustrate the capabilities of the Twin4Build platform in providing actionable insights. Beyond resolving design inefficiencies, the platform demonstrated its value as a performance benchmarking tool. Metrics such as thermal comfort, energy consumption, and system responsiveness were evaluated and optimized through data-driven simulations.

Key performance metrics achieved:

(1) Thermal Comfort Improvement: Thermal discomfort violations were reduced by up to 84%, significantly improving occupant comfort.

(2) Energy Efficiency: Adjustments to the heating system reduced operational inefficiencies and ensured better energy distribution within the facility.

(3) System Responsiveness: Real-time updates to the semantic model allowed for rapid scenario testing and optimization, minimizing delays in implementing corrective actions.

(4) Operational Insights: The integration of semantic and simulation models provided a unified view of system performance, enabling a deeper understanding of operational dynamics and facilitating proactive maintenance strategies.

This case study highlights the transformative potential of digital twin technology in optimizing building energy systems. By seamlessly integrating semantic modeling, real-time data, and advanced simulation capabilities, the Twin4Build platform demonstrates a tangible pathway toward smarter, more efficient, and adaptive building operations. It provides a benchmark for leveraging digital twins to achieve sustainable performance and operational enhancement.

5. Technical discussion, comparison, and analysis

5.1. Key technical aspects of digital twin deployment

The deployment of digital twins in construction involves integrating complex data systems, real-time analytics, and advanced computational methods [11]. To support the diverse applications outlined, DTs require robust frameworks that align with core digital twin components, such as IoT integration, BIM, and cloud computing. In Denmark, standardization efforts and adherence to frameworks like NGSI-LD and SAREF [4] have been pivotal, enabling greater interoperability and making Danish DT projects some of the most scalable in Europe.

The use of IoT sensors is crucial for capturing granular, real-time data across construction sites, feeding into virtual models that continuously mirror the physical world. Yet, achieving reliable data flow remains a challenge due to high variability in construction environments, particularly with data accuracy and signal stability. Recent developments in edge computing have helped address latency issues by enabling faster, localized data processing, a critical advancement for construction sites where immediate data feedback is necessary for tasks such as safety monitoring and environmental assessments [12].

5.2. Comparative analysis of DT applications and benefits

- Safety and Risk Management: Safety monitoring via DTs involves real-time tracking of worker activity, equipment status, and site conditions, with predictive analytics helping to proactively manage potential hazards. Comparatively, Denmark's DT safety initiatives are highly advanced, leveraging AI-driven algorithms to predict and mitigate risks in near real time. This capability is often seen in collaborative projects involving companies like COWI and technology partners who deploy DTs for hazard analysis and safety compliance. However, while these systems significantly improve safety, smaller firms face challenges in accessing similar advanced technologies due to cost and skill requirements.
- Project Optimization and Resource Efficiency: Denmark's DT applications are heavily focused on project optimization and resource efficiency. Danish projects frequently integrate BIM with IoT and AI to create comprehensive models that track progress, allocate resources, and reduce material wastage. Recent research and practical applications allow for establishing real-time resource monitoring that aligns construction progress with material requirements, reducing idle times and excess inventory. This integration directly contrasts with traditional methods that rely on manual tracking and retrospective analysis, making DT-driven approaches substantially more efficient and reducing overall project timelines.
- Environmental Sustainability: The role of DTs in advancing sustainability goals is particularly evident in Denmark's commitment to the Green Digital Transition initiative, where DTs are deployed to monitor emissions, optimize energy consumption, and track waste throughout the construction process. By continuously monitoring energy usage and environmental impact, Danish DTs actively support circular economy principles. Comparatively, while other regions implement DTs to reduce carbon footprints, Denmark's strong alignment with national sustainability policies amplifies these efforts. As a result, Danish DTs are more oriented towards lifecycle assessment, creating opportunities for end-to-end waste management that many global counterparts have yet to fully adopt.

5.3. Analysis of current challenges

- Data Integration and Interoperability: Integrating diverse data sources remains a challenge, as DTs in construction must combine BIM, sensor, and environmental data seamlessly [13]. Denmark's approach to standardization, notably through the adoption of NGSI-LD and SAREF, addresses some interoperability issues. However, despite these frameworks, practical challenges persist in reconciling varying data formats and protocols across different construction systems. Comparatively, Denmark's focus on open standards positions it ahead of many countries, yet broader adoption of interoperable DT solutions requires further progress in industry-wide standardization.
- Security and Data Privacy Concerns: DT systems in construction sites capture a range of sensitive data, from equipment usage to workforce movements, which raises

significant concerns about data security and privacy. In Denmark, regulatory compliance and robust cybersecurity practices have addressed some of these concerns, yet ensuring privacy in real-time applications remains an area of focus, particularly as the complexity of DT models increases. Comparing this with other European regions, Denmark is relatively proactive in aligning DT applications with GDPR and other regulatory standards, though continuous updates are required to manage evolving security threats in highly connected construction environments.

- Cost Implications and Scalability: Implementing DT technology at scale is an expensive endeavor, especially for smaller construction firms that may lack the resources for extensive DT integration. Danish initiatives, supported by programs like the Green Digital Transition, attempt to mitigate these costs through funding and standardization efforts. However, costs related to infrastructure, sensor networks, and specialized skills still limit the scalability of DT technology. This issue is not unique to Denmark; across the industry, DT deployment remains constrained by financial and operational challenges, though ongoing advancements in open-source platforms and modular DT components offer potential cost-saving avenues.

6. Future trends in digital twin technology for construction in Denmark

The future of DT technology in Denmark's construction sector will likely see deeper integration with AI, machine learning, and cloud-based analytics, creating more autonomous DT systems capable of independent decision-making and predictive maintenance. This future aligns with Denmark's overarching goals of sustainable urban development, where DTs are expected to play a central role in promoting energy efficiency, reducing emissions, and optimizing resource use across the built environment. Comparing Denmark's approach to other leaders in DT adoption, Denmark's proactive stance on policy support, standardization, and sustainability-centric DT deployment provides a model that could be replicated or adapted by other nations aiming for similar environmental and technological outcomes. Below are some key aspects to consider for a more effective and impactful building digital twins implementation in the future:

6.1. Advanced AI and predictive analytics

The integration of AI and machine learning (ML) into DT technology represents a transformative shift in Denmark's construction sector [14]. These advancements promise to create more autonomous systems capable of making real-time decisions, optimizing resource use, and proactively addressing issues, aligning with Denmark's goals of sustainable development and net-zero carbon emissions. AI and ML algorithms are anticipated to significantly enhance the predictive capabilities of DTs. By analyzing extensive datasets from sensors, IoT devices, and historical project records, future DT systems will provide insights that extend beyond maintenance and fault detection. For instance, advanced models will anticipate equipment failures or material degradation with exceptional accuracy, enabling timely interventions. These systems will also monitor site conditions and worker behavior to identify hazards in real time, thereby enhancing workplace safety. Automated detection of deviations from design specifications during construction will help minimize rework and delays, while the integration of natural language processing (NLP) could allow DTs to analyze unstructured data, such as project reports or maintenance logs, refining decision-making processes and further boosting operational efficiency.

6.2. Integration with sustainable construction and circular economy

Future DTs will also play a crucial role in advancing Denmark's shift toward a circular economy [15]. AI-driven models will optimize material usage by providing recommendations based on lifecycle assessments, minimizing waste, and improving recycling processes. Dynamic adjustments to resource use during construction phases will reduce material wastage and energy consumption. Simultaneously, continuous monitoring of materials and components, from procurement to deconstruction, will ensure maximum reuse and minimal environmental impact. These systems will also incorporate AI to calculate and visualize carbon emissions in real time, aiding stakeholders in adhering to green building standards and policies while ensuring alignment with Denmark's environmental objectives.

6.3. Enhanced interoperability and standards development

Seamless interoperability is another critical focus for the next generation of DT systems. Denmark's efforts to adopt open standards such as NGSI-LD and SAREF will facilitate data sharing across platforms and sectors, with AI playing a pivotal role in achieving this goal. AI algorithms will standardize and map data from diverse sources, ensuring compatibility and usability across different systems. By interpreting complex relationships between data entities through AI-based ontologies, these systems will enhance the accuracy of decision-support mechanisms. Additionally, intelligent data integration will bridge silos between sectors such as energy, transportation, and urban planning, fostering a unified approach to smart city development [16].

6.4. Virtual and augmented reality integration

Finally, integrating virtual and augmented reality (VR and AR) into DT workflows offers an interactive and immersive approach to project management. AI will amplify these technologies by enabling dynamic simulations and real-time overlays. For example, AI-powered VR environments will simulate construction scenarios, allowing stakeholders to test designs and processes before implementation. On-site workers equipped with AR tools can receive precise instructions, automated quality checks, and safety alerts, all informed by AI-driven contextual data. This integration ensures precision, reduces human errors, and provides stakeholders with a more tangible connection to project progress.

In summary, the future of digital twins in Denmark's construction sector lies in their evolution into AI-driven, highly intelligent systems that optimize resources, enhance sustainability, and foster collaboration across industries. By aligning technological advancements with environmental and societal goals, Denmark positions itself as a global leader in sustainable construction innovation.

7. Conclusion

Digital twins (DTs) hold transformative potential for Denmark's construction industry, offering powerful solutions for real-time monitoring, predictive maintenance, safety enhancement, and sustainability. While challenges remain around data integration, security, costs, and skills development, the advantages of DTs in improving site operations and achieving environmental objectives are undeniable. With continued investment in research, infrastructure, and workforce training, Denmark is poised to lead the adoption of DTs in sustainable construction.

Aligning with Denmark's vision for a digital, sustainable future, DT adoption supports both industry advancement and national goals for carbon neutrality. As Denmark builds on its achievements and addresses the technological and operational hurdles, DTs will play a vital role in shaping the future of construction.

Denmark's vibrant digital twin ecosystem—driven by cutting-edge research initiatives, active government support, and collaboration across the industry—exemplifies how DT technology can revolutionize construction site monitoring and project optimization. As the industry increasingly adopts DTs for diverse uses, from safety management to sustainable building practices, Denmark sets a global benchmark for digital transformation, demonstrating the path toward a sustainable and digitized construction industry.

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Conflicts of interests

The authors declare that they have no conflicts of interests.

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