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MAINTENANCE AND DIGITAL TWIN TECHNOLOGY FOR SMART BUILDING MANAGEMENT

Álvaro Vale e Azevedo*, M. João Falcão Silva*, Filipa Salvado*
* LNEC – National Laboratory for Civil Engineering, Lisbon, Portugal
ava@lnec.pt
mjoaofalcao@lnec.pt
asalvado@lnec.pt

ABSTRACT

As infrastructures age and urban populations grow, maintaining structural integrity and operational efficiency has become an increasingly pressing challenge. Traditional maintenance practices, often based on pre-defined theoretical plans, can result in inefficient resource allocation, higher costs, and an increased risk of unforeseen failures. Digital Twin technology provides a dynamic virtual representation of physical assets, enabling real-time simulations, condition-based forecasting, and scenario analysis. When performance data is available (collected from integrated infrastructure monitoring), this approach allows for continuous tracking of key indicators related to the structural service life of assets. This represents a significant evolution in infrastructure management, supporting more informed and strategic decision-making. It enables the adoption of a proactive maintenance approach, improving operational efficiency, reducing risks, and extending the lifespan of urban infrastructure. The integration of maintenance strategies with Digital Twin technology also aligns with sustainability principles by minimizing resource waste and reducing emissions associated with emergency corrective interventions.
This paper proposes the integration of maintenance strategies with Digital Twin technology to enhance asset and facility management in the Architecture, Engineering, Construction, and Operation (AECO) sector, contributing to the advancement of building and infrastructure management and positions emerging technologies as essential tools for future-ready cities. The study outlines implementation strategies, performance metrics, and scalability considerations applicable to a wide range of infrastructure systems.

KEYWORDS

Maintenance, Digital twin, smart building management

1. INTRODUCTION

The rapid growth of urban populations and the resulting increase in infrastructure demand have intensified the challenges of maintenance and asset management in the Architecture, Engineering, Construction, and Operations (AECO) sector [1]. As existing infrastructures age, ensuring structural integrity and operational efficiency has become a priority for both public and private stakeholders [2,3,4]. Traditional maintenance methods, often based on theoretical plans or fixed schedules, are limited in addressing complexity and unpredictability of asset lifecycles. This can lead to inefficient resource allocation, high costs, and a higher risk of unplanned failures [5,6,7,8]. In this context, emerging technologies offer new possibilities for transforming urban asset management. Among these, the Digital Twin stands out. It is defined as a dynamic virtual representation of a physical asset, capable of reproducing its operating conditions in real time through the integration of sensors data, computational models, and simulation algorithms. Unlike static models, Digital Twins enable continuous monitoring of key performance indicators, forecasting based on real conditions, and degradation analysis or failure scenarios [9,10]. The integration of maintenance strategies and Digital Twin technology represents a significant advance in the AECO sector, enabling the transition from reactive practices to proactive and predictive approaches. This translates into greater operational efficiency, risk mitigation, and extended asset lifespans. Moreover, this integration aligns with sustainability principles by reducing resource waste and minimizing emissions associated with emergency and corrective interventions [11,12,13].
This paper examines the opportunities and challenges of incorporating Digital Twins into maintenance processes, discussing implementation strategies, performance metrics, and scalability possibilities. The aim is to contribute to the advancement of asset management in the AECO sector, positioning the Digital Twin as a strategic tool for the development of resilient and future-ready cities.

2. FRAMEWORK

2.1 Maintenance

Asset maintenance is a critical component of infrastructure management, directly influencing reliability, safety, and performance throughout the lifecycle. Traditionally, maintenance models fall into three main categories: corrective, preventive, and predictive [14,15,16,17]. Corrective maintenance consists of repairing failures only after they occur. Although straightforward, this approach carries high risks, as unexpected failures can generate significant costs and compromise the safety of users and operations [15,18,19]. Preventive maintenance seeks to reduce the likelihood of failures through scheduled inspections and interventions. Although this increases system reliability, it is not always efficient, since it may result in unnecessary replacements and additional costs [16,20]. More recently, predictive maintenance has gained prominence. Based on continuous asset monitoring it uses performance data to forecast failures before they occur. This approach is particularly relevant when combined with digital technologies, smart sensors, and real-time data analysis [15,16,21].

2.2 Digital Twin

The term Digital Twin was originally introduced in the context of the product lifecycle management, and later expanded to multiple sectors, including manufacturing, healthcare, energy, and infrastructure. A Digital Twin is defined as a digital replica of a physical system, continuously updated through the integration of data collected in real time [22]. Its main characteristic is its dynamic nature: instead of representing a static model, it reflects the behaviour and actual state of the asset over time. This bidirectional connection between the physical and virtual systems enables advanced simulations, failure prediction, scenario analysis, and decision support [23]. In the AECO sector, Digital Twins are often associated with Building Information Modelling (BIM), which provides the geometric and informational basis of assets. However Digital Twins evolve beyond BIM by integrating real-time data from sensors and monitoring systems. This integration enables a continuous cycle of information collection, analysis, and feedback, supporting intelligent infrastructure and buildings management [24].

2.3 Integrating Maintenance and Digital Twin

The integration of maintenance strategies with Digital Twins is an iterative process as represented in Figure 1. The adoption of Digital Twins in urban infrastructure maintenance has expanded in recent years, driven by the need to optimize resources, reduce unexpected failures, and support sustainable practices. Combined with IoT sensors, they allow real-time monitoring of critical parameters such as vibration, temperature, structural deformations, and energy consumption [22,24]. Case studies highlight their application in bridges, highways, railways, and smart buildings. For example, Digital Twins have been used to monitor the structural integrity of bridges in real time, enabling early interventions and extending the infrastructure's lifespan. Similarly, in commercial buildings, they have been used to optimize HVAC and energy systems, resulting in significant reductions in operating costs [23].

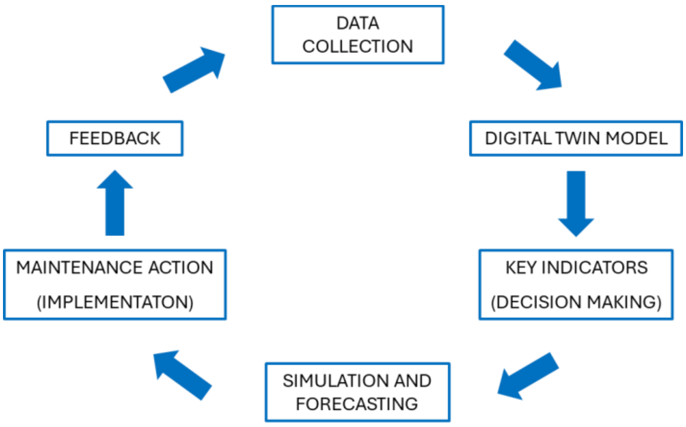

Figure 1 – Integrating maintenance and digital twin

Despite these advances, challenges remain for large scale adoption, namely: i) interoperability between different platforms and data standards; ii) high initial costs for implementing sensors, software, and digital infrastructure; and iii) the need for professional training to interpret complex data and make informed decisions based on digital models. Nevertheless, Digital Twins are expected to consolidate itself as a key technology in asset management, mainly due to its ability to integrate maintenance, operation, and sustainability into a single digital ecosystem [22,23,24].

3. METHODOLOGY

The proposed methodology follows an asset-centric, risk-oriented approach, supported by emerging digital technologies, with emphasis on integrating maintenance strategies and Digital Twin modelling. This process is developed in progressive stages, involving data collection, virtual model construction, scenario simulation, and decision-making support [10,22,24]. At its core, the methodology establishes a continuous cycle of integration between the actual performance of urban assets and their digital representation. This cycle consists of four steps (Figure 2).

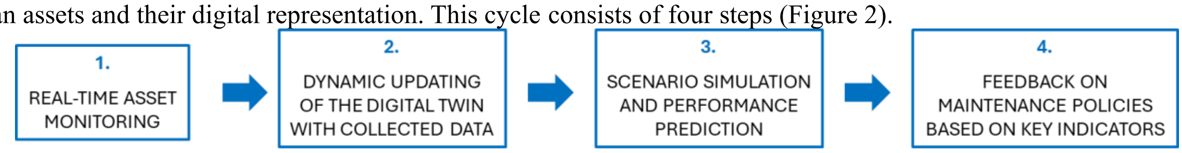

Figure 2 – Integration between the actual performance of urban assets and their digital twin

Through this approach, maintenance evolves from reactive or preventative to predictive and proactive, guided by digitally identified evidence and risks [10,11,15]. Table 1 describes the steps for implementing and operationalizing the methodology.

STEPS	DESCRIPTION
1. Data Collection through Integrated Monitoring	– IoT (Internet of Things) sensors are installed on critical assets to collect data on vibration, deformation, humidity, temperature, and structural load. – Drones and LiDAR are used for detailed inspections of hard-to-reach areas. – GIS (Geographic Information Systems) consolidate and georeferenced information.
2. Construction of the Virtual Model (Digital Twin)	– Develop a BIM (Building Information Modelling) model. – Parameterization of models with engineering data, maintenance history, and registration records. – Connection of models to dynamic databases that receive real-time updates.
3. Execution of simulations and performance prediction	– Modelling of structural failure scenarios, degradation throughout the life cycle, and exposure to natural disasters (floods, landslides, heat waves). – Application of Machine Learning algorithms for failure prediction and risk assessment. o Assessment of direct (structural collapse) and indirect (interruption of essential services) impacts.
4. Decision-making based on key indicators	– Definition of maintenance policies prioritized by asset criticality. – Optimized allocation of financial and human resources. – Adoption of mitigation and resilience strategies for high risks assets.

Table 1 – Methodology implementation and operationalization

Table 2 presents complementary tools and technologies, to be used by this methodological process.

TOOLS/TECHNOLOGIES	DESCRIPTION
IoT sensors	Devices embedded in assets for continuous collection of structural and environmental data.
BIM models	Used to create detailed digital models of urban assets.
GIS systems	Spatial integration of data and identification of territorial vulnerabilities.
Data analysis platforms	Big Data and Machine Learning applied to failure prediction.
Cloud infrastructure	Storage and processing of large volumes of data in real time.

Table 2 – Tools and technologies

This structured methodology ensures a cyclical flow of monitoring, modelling, analysis, and decision-making, supported by digital technologies and aimed at increasing the resilience of urban infrastructures to risks and natural disasters.

4. IMPLEMENTATION STRATEGIES

The integration of maintenance strategies with Digital Twin technology requires a systematic approach that considers technical, organizational, and strategic aspects. For feasibility in the AECO sector, a set of guidelines should be followed [6,8]. The first step is the integration into existing operations and maintenance processes. This involves the following steps [6,8,12]: i) digital twins should be gradually incorporated into already established operations and maintenance routines; ii) digital twins functions as an additional layer of intelligence, without immediately replacing conventional practices, but complementing them with real-time monitoring, performance predictions, and risk analysis; and iii) integration involves adjusting workflows so that data captured by sensors and digital models are translated into useful operational information for decision-making. After that, phased adoption models are suggested, and can follow a progressive process described in Table 3.

Regarding technical and organizational challenges, the large-scale adoption of Digital Twins for maintenance faces critical barriers that need to be addressed, namely: i) system interoperability (integration between BIM, GIS, IoT, and analytics platforms still presents compatibility limitations and common standards need to be established); ii) workforce training (operations and maintenance teams must acquire digital skills, including data interpretation, use of predictive platforms, and interaction with digital models); and iii) high initial costs (sensors, digital platforms, and data infrastructure require considerable investment and returns are expected in the medium term, the initial phase can be a hurdle for municipalities with limited resources) [6,12].

STEPS	DESCRIPTION
Pilot projects	– Initial application on critical or highly visible assets (e.g., a strategic bridge or a water treatment plant). – Assessment of benefits in terms of cost, efficiency, and resilience.
Controlled expansion	– Gradual scaling to different infrastructure types (transportation, energy, water infrastructure systems, public buildings). – Integration with multiple platforms (BIM, GIS, IoT).
Full scalability	– Methodology incorporation as a standard practice in urban maintenance plans. – Structuring public-private partnerships to support large-scale adoption.

Table 3 – Phased adoption models

Depending on local contexts and technological maturity of cities, implementation can be conducted at three complementary levels: i) technical-operational (sensor installation, algorithm development, and integration with BIM/GIS models); ii) organizational (workflows adaptation, continuous team training, and creation of risk-based decision-making centres); and iii) strategic and political (inclusion in public policies, urban regulations, and innovative financing mechanisms) [8,12].

5. PERFORMANCE METRICS AND EXPECTED RESULTS

Defining performance metrics is essential to evaluate the effectiveness of integrating maintenance strategies with Digital Twin technology. Key Performance Indicators (KPIs) are structured across four core dimensions (operational, economic, sustainability, and resilience), incorporating both quantitative and qualitative criteria and are described in Table 4 [13,16].

METRICS	DESCRIPTION
Operational efficiency	– Mean Time Between Failures: Increase in the intervals between failures. – Asset Availability: Proportion of time infrastructure remains operational. – Emergency Response Time: Reduction in time between fault detection and repair.
Economic efficiency	– Maintenance Cost Reduction: Comparison of corrective versus preventive maintenance costs. – Return on Investment: Financial return derived from Digital Twins application. – Resource Optimization: Percentage savings in materials, and labour inputs.
Sustainability and environment	– Emissions Reduction: Calculation of the CO_2 reduction generated by the prevention of emergency works and the optimized use of resources. – Extended Asset Lifecycle: Increase in the average durability of urban infrastructure, reducing the need for frequent replacements. – Contribution to global sustainability goals: Alignment with UN SDGs, focusing on sustainable cities, climate action, and responsible consumption.

Urban resilience and social security	– Reduction in unexpected failures: Percentage reduction in unforeseen critical events. – Recoverability: Time needed to restore functionality after disruptive events. – Reliability of predictive models: Degree of accuracy of simulations compared to real risk conditions.
Proposed KPIs	1. Maintenance cost reduction (percentage savings achieved compared with traditional scenarios). 2. Reduction in unexpected failures (proportion of critical events avoided after implementing the methodology). 3. Asset life extension (average number of years added to the infrastructure lifecycle). 4. Operational and energy efficiency (reduced energy consumption and higher productivity of monitored assets). 5. Emissions reduction and alignment with sustainability goals (avoided emissions metrics, CO_2 equivalent, and contributions to environmental policies).

Table 4 – Performance metrics

Table 5 presents the expected results, according to the four dimensions described and according to the KPIs defined [13,16].

RESULTS	DESCRIPTION
Operational	– Reduction in unexpected failures: 20-40% reduction in critical incidents is expected, due to the predictive capabilities of digital simulations and real-time monitoring. – Increased operational efficiency: Critical assets, such as bridges, transportation systems, and power grids, will be able to maintain availability rates above 95%. – Energy efficiency: Continuous adjustments to asset performance should reduce operational losses, resulting in estimated 10-15% energy savings.
Economic	– Maintenance cost reduction: 20–30% savings in maintenance costs, as emergency interventions, which are generally more expensive, are replaced by planned actions. – Asset life extension: 5-10 years estimated average gain in the life cycle of strategic infrastructure, postponing large investments in replacement or reconstruction. – Return on investment (ROI): in the medium term (5 to 7 years), the initial costs of implementing the technology are expected to be offset by reduced operating expenses.
Sustainability	– Reduction in CO_2 emissions: 10-20% estimated emissions reduction related to avoided emergency works and optimized material transportation. – Reduced waste generation: due to increased efficiency in material use, with reduced waste from fewer unplanned corrective interventions. – Alignment with global sustainability goals: direct contribution to the Sustainable Development Goals (SDGs), especially: SDG 9 (Industry, Innovation and Infrastructure); SDG 11 (Sustainable Cities and Communities); and SDG 13 (Climate Action).
Resilience	– Greater public safety: reduced risk of structural collapse in essential assets. – Continuity of essential services: reduced disruption time for transportation, water supply, energy, and sanitation after disasters. – Recoverability: expected to reduce average recovery time after extreme events by up to 30%, making cities better prepared to face natural disasters.

Table 5 – Expected results

6. CONCLUSION

This paper has shown that integrating maintenance strategies with Digital Twin technology represents a milestone in the evolution of asset management in the AECO sector. By transforming the way infrastructure is monitored, analysed, and managed, the Digital Twins technology enable the transition from reactive and prescriptive practices to proactive and predictive approaches, improving operational efficiency and significantly reducing the risk of unexpected failures.

The results discussed indicate that this integration offers multiple benefits, including optimizing resource allocation, lower maintenance costs, extended asset lifespans, and improved resilience of urban infrastructure. Furthermore, aligning with sustainability principles, it reduces material waste and emissions associated with emergency corrective interventions. These outcomes reinforce the role of Digital Twin technology as an essential tool for developing smart and sustainable cities.

Nonetheless, several challenges remain, such as systems interoperability, high initial implementation costs, the need for professional training, and the adaptation of governance models to support advanced digital technologies. These challenges highlight the importance of gradual adoption strategies, starting with pilot projects and evolving to broader application scales.

Ultimately, the Digital Twin technology should be regarded not merely as a technological innovation, but as a new paradigm for urban asset management, capable of generating economic, social, and environmental value. By integrating with maintenance strategies, it expands the scope of planning and decision-making in the AECO sector, paving the way for strengthening urban resilience and building cities better prepared for future challenges.

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