HVAC System Performance in Educational Facilities: A Case Study on the Integration of Digital Twin Technology and IoT Sensors for Predictive Maintenance

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Abstract: This research paper delves into the pivotal role of Digital Twin technology and Internet of Things (IoT) sensors in revolutionizing predictive maintenance for HVAC systems within educational environments, exemplified by a comprehensive case study at the Papa Giovanni XXIII school in Nichelino, Italy. Marking a significant departure from traditional building information modeling practices, Digital Twin technology introduces a real-time, dynamic representation of building systems, enabling proactive rectification of system inefficiencies and failures to improve building performance, occupant well-being, and sustainability. This study showcases the pioneering implementation of Digital Twin technology integrated with IoT sensors, leveraging Autodesk Tandem to offer invaluable insights into system health and optimal maintenance timing. The integration facilitated comprehensive system monitoring and analysis, leading to significant outcomes. Specifically, the implementation resulted in a 15% reduction in energy consumption and a 20% improvement in system reliability. Additionally, there was a notable decrease in unplanned maintenance interventions, highlighting the efficacy of predictive maintenance strategies enabled by Digital Twin technology. These findings validate the practical applicability of Digital Twin technology in enhancing HVAC system performance and operational efficiency. The study underscores the transformative potential of this digital leap in the construction sector's ongoing evolution toward greater digitalization. By addressing technological complexities and substantial initial investments, this research paves the way for future advancements in smart building technologies, making a crucial contribution to the emerging discourse on Digital Twins in construction. **DOI:** 10.1061/JAEIED.AEENG-1855. © *2025 American Society of Civil Engineers*.

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Introduction

Over past decades, the construction industry has embarked on a profound shift toward digitalization, with the objective of enhancing the efficiency, sustainability, and comfort of built environments (Watson 2011). Leading this transformative journey is building information modeling (BIM), a revolutionary approach that has fundamentally changed design, construction, and maintenance practices by encapsulating the physical and functional characteristics of buildings (Bynum et al. 2013; Saieg et al. 2018). However, it is the advent of Digital Twin technology—significantly augmented by the Internet of Things (IoT)—that represents a groundbreaking leap forward from BIM's capabilities. This innovative approach offers a dynamic and interactive model that reflects the real-time status of building systems, heralding a new era in predictive maintenance strategies designed to proactively address system inefficiencies and failures, thereby optimizing building performance and enhancing occupant well-being (Boje et al. 2020).

The necessity for maintaining optimal indoor environments is particularly pronounced in educational settings, where there is an undeniable link between the health and comfort of occupants and their learning outcomes. HVAC systems are critical in this context, because they significantly influence a building's energy consumption and operational costs (Lee et al. 2012; Wang et al. 2015). Traditional maintenance strategies, which are mostly reactive or based on scheduled checks, often result in inefficiencies, unexpected failures, and significant operational disruptions. In contrast, predictive maintenance—enabled by Digital Twin technology and informed by real-time data analytics—takes a proactive stance. This innovative strategy not only improves system reliability and efficiency but also promotes energy conservation and aligns with broader sustainability goals (Mi et al. 2021).

Despite the clear advantages of Digital Twin technology, its adoption within the construction sector, particularly for predictive maintenance purposes, is confronted with significant challenges. These include the technology's inherent complexity, the substantial initial investments required, and a general lack of expertise among industry professionals. Furthermore, the historically slow pace of digital transformation within the sector amplifies these challenges, highlighting the urgent need for convincing, tangible demonstrations of Digital Twins' utility in building management (Opoku et al. 2023).

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This study seeks to bridge a critical gap in the research by showcasing a pioneering application of Digital Twin technology in the Papa Giovanni XXIII school in Nichelino, Italy. This case study not only demonstrates the practical feasibility and advantages of employing Digital Twins (DT) but also elaborates on the integration process of IoT sensors for comprehensive system monitoring. By analyzing key operational parameters—such as airflow rate, air velocity, and temperature—during periods of suboptimal performance, the research provides essential insights into the system's health and identifies the most opportune moments for maintenance. Utilizing Autodesk Tandem for data simulation and analysis, this study underlines the potential of Digital Twins to streamline maintenance processes, reduce operational interruptions, and ensure continuous system operation.

Moreover, this investigation explores the broader implications of predictive maintenance within the field of architectural engineering, examining its impact on building sustainability, occupant comfort, and life-cycle cost management. Additionally, by identifying the barriers to the widespread adoption of Digital Twins in the construction industry, this research suggests strategies to overcome these obstacles, paving the way for further advancements in smart building technologies.

Therefore, this study contributes to the nascent but rapidly growing body of literature on Digital Twins in construction, offering an in-depth analysis of their practical application, benefits, and future potential. Because buildings play a crucial role in our daily lives, ensuring the health and efficiency of their systems is paramount. Through the lens of the Papa Giovanni XXIII school case study, this research illuminates the transformative impact of Digital Twin technology, marking a significant milestone in the digital evolution of the construction sector.

Literature Review

Digital Twin Technology in Construction

The integration of Digital Twin technology into the construction industry represents a pivotal shift, marking a significant evolution from its aerospace and manufacturing origins toward enhancing efficiency, sustainability, and operational excellence in construction projects. This section reviews critical contributions to the literature, highlighting the diverse roles and transformative potential of Digital Twin technology in the construction domain.

A comprehensive review reveals the essential contributions and dimensions of Digital Twin technology that align with this transformative journey. Notably, the role of Digital Twins in smart construction and digital urban planning emerges as a key area with the potential to streamline processes and manage the complexities associated with building and urban infrastructure operations (Fuller et al. 2020).

Salem and Dragomir (2022) explored the utility of Digital Twins in facilitating smart construction practices and the development of digital cities, illustrating the progression from virtual models to sophisticated systems integrating artificial intelligence (AI), machine learning, and comprehensive life-cycle management. This evolution is crucial for enhancing construction project management outcomes by automating operations and deepening the understanding of project dynamics. Similarly, Shah (2023) investigated the multifaceted applications of Digital Twin technology across civil engineering and construction disciplines. From infrastructure development to structural health monitoring and improving energy efficiency, Shah highlighted how Digital Twins acted as a unifying platform to address the sector's challenges, fostering efficiency and sustainability.

Khallaf et al. (2022) conducted a systematic examination of Digital Twins' applications within construction, identifying their benefits across life-cycle analysis, facility management, and disaster response. Their findings underscore the technology's ability to enhance stakeholder engagement, reduce operational costs, and automate key functions such as energy demand management. This foundational research opens new directions for leveraging Digital Twins' potential further. In contrast, Shahzad et al. (2022) focused on the integration of Digital Twins in built environments, emphasizing the synergy between Digital Twins and other digital technologies. Their analysis shed light on both the challenges and the opportunities presented by Digital Twins in the construction and maintenance of built assets, providing valuable insights into the digital transformation of asset delivery and operation.

Hou et al. (2020) highlighted the application of Digital Twin technologies in enhancing construction workforce safety, pointing out the effectiveness of Digital Twins in mitigating safety risks and the industry's hesitancy in adopting such technologies. This gap highlights the need for innovative approaches and strategic implementation plans to encourage the widespread acceptance and application of Digital Twins in construction safety protocols.

This evolution is further enriched by the integration of BIM processes and the Leadership in Energy and Environmental Design (LEED) certification system, emphasizing a growing focus on sustainable building practices within the Architecture, Engineering, and Construction (AEC) sector. Di Gaetano et al. (2023) introduced an innovative approach to integrating BIM with LEED certification, aimed at enhancing sustainable design strategies within the AEC sector. Meanwhile, Cascone (2023) analyzed the synergies between LEED certification and BIM, particularly in sustainable development and parametric design contexts. This research outlined various integration methods between LEED and BIM at the early design phase, highlighting the potential for automating LEED certification within BIM processes.

Despite challenges such as high implementation costs, technological complexities, and a pronounced skills gap involved in the adoption of Digital Twin technology in the construction industry, the body of literature signals an optimistic shift toward overcoming these barriers. As technology costs decrease and digital proficiency within the sector rises, ongoing research and development efforts are increasingly poised to foster a more cohesive, efficient, and sustainable construction landscape.

IoT Sensors in Building Maintenance

The integration of IoT technology into the realm of building maintenance signifies a transformative leap toward practices that are not only more efficient but also cost-effective and centered around the needs of occupants. The emerging literature underlines the crucial role of IoT in shifting building maintenance from traditional, reactive models to proactive and predictive paradigms (Kumar et al. 2021). This shift is particularly emphasized through the integration of IoT sensors with advanced analytics and digital technologies, highlighting a significant move toward smarter building management practices.

Casini (2022) delved into the strategic significance of IoT devices in the optimization of building operations and maintenance (O&M). His research points to a notable reduction in energy consumption and maintenance costs, underscoring the synergistic potential of Digital Twin technology, IoT, BIM, and AI. This ensemble is portrayed as a cornerstone for the future of O&M, with extended reality (XR) technologies spotlighted for their ability to enhance smart building management and support informed decision-making, particularly within the ambit of smart cities.

Lawal and Rafsanjani (2022) provided a comprehensive overview of IoT's applications across a variety of settings, from residential to commercial, sorting studies into domains such as home automation, intelligent energy management, and healthcare facility optimization. They illuminated key challenges in IoT's implementation, including issues related to technology integration, data management, and privacy concerns, and advocated for targeted research efforts to surmount these barriers. This highlights the imperative to fully leverage IoT's potential in fostering better building environments.

Harkonen et al. (2023) explored the concept of building smartness and the significant impact of IoT on enabling interoperable building automation systems. They acknowledged the power of IoT to enhance building intelligence but also cautioned against potential inconsistencies. Their recommendation for the specification of technical building systems aimed to address these performance gaps, underscoring the importance of clarity in schematics for improving building efficiency and sustainability.

Yaïci et al. (2021) concentrated on the utilization of IoT applications to optimize building energy usage and mitigate greenhouse gas emissions, with a special focus on heating systems. Their analysis of IoT's core components—sensors, actuators, and control strategies—revealed the technology's promise in substantially reducing energy consumption while simultaneously elevating user comfort.

Hannan et al. (2018) investigated the nascent field of the Internet of Energy (IoE), built upon IoT technologies, as a transformative agent in building energy management systems (BEMS). They discussed traditional BEMS limitations and the potential of IoE solutions to surpass these challenges through the use of advanced controllers and technologies. The review advocated for a focus on sophisticated IoE solutions to further BEMS advancements, identifying technical challenges such as data loss and network issues and suggesting avenues for future improvement.

In conclusion, this literature review section emphasizes the pivotal role of IoT technology in evolving building maintenance practices. Despite challenges such as data integration, security concerns, and the need for interoperability, the literature strongly suggests a future where IoT-enabled smart buildings achieve unprecedented levels of efficiency, sustainability, and occupant satisfaction. This transition from theoretical exploration to practical application within the architectural engineering domain lays the groundwork for an in-depth examination of predictive maintenance strategies, further enriching the discourse on smart building technologies and their impact on creating sustainable and occupant-focused built environments.

Predictive Maintenance in Architectural Engineering

The field of architectural engineering is witnessing a paradigm shift toward predictive maintenance, driven by the synergistic integration of IoT sensor data, Digital Twin technology, and advanced analytics (Villa et al. 2021). This transformative approach signifies a departure from traditional maintenance practices, moving toward a model that is informed by data. This shift enables the early detection of system issues, enhances system performance, and extends the operational lifespan of building infrastructure, marking a new era in building management strategies.

Coupry et al. (2021) investigated the application of DT and XR devices within the context of smart buildings to streamline maintenance procedures. Their study highlighted the potential of leveraging DT with XR technologies to enhance maintenance operations, despite acknowledging the hurdles in implementation. This integration of BIM-based Digital Twins with XR technologies was identified as a promising predictive maintenance paradigm, potentially revolutionizing operations within smart buildings.

Hosamo and Hosamo (2022) delved into the fusion of Digital Twin technology with 3D laser scanning techniques for bridge maintenance, illustrating a significant step toward predictive maintenance. This innovative integration provided a comprehensive, interactive representation of physical structures, enabling early problem identification and facilitating strategic maintenance planning. Such an approach represents a substantial advancement in the maintenance of civil infrastructure, employing Digital Twin technology to improve operational insights and support informed decision-making.

Casini (2022) examined the convergence of XR with Digital Twin technology and IoT devices during the operation and maintenance phases of smart buildings. The study posited that the combination of XR, DT, and IoT can significantly enhance maintenance efficiency, promote proactive maintenance practices, and enable predictive functionality. This interdisciplinary approach highlighted the transformative impact of these technologies in optimizing building operations and life-cycle management, showcasing a path toward more efficient and proactive building maintenance strategies.

Aivaliotis et al. (2019) proposed a requirement-driven roadmap for automating predictive maintenance via the standardization of Digital Twin technologies. They identified Digital Twins as a key solution to the challenges of scalability and explainability inherent in traditional predictive maintenance methodologies. The authors advocated for focused research efforts to develop a cohesive framework for predictive maintenance with Digital Twins, aiming to streamline these processes across the industry and enhance the efficacy of maintenance strategies.

Hosamo et al. (2022) explored the application of Digital Twin technology within the Architecture, Engineering, Construction, and Facility Management (AEC-FM) industry, emphasizing the blending of physical and digital realms. They presented an overview of current trends, identified existing gaps, and suggested a conceptual framework for Digital Twins in building management, laying the groundwork for future research in this area.

This literature review elucidates the transformative impact of predictive maintenance in architectural engineering, facilitated by the integration of IoT, Digital Twin technology, and advanced analytics. This convergence not only facilitates the early detection of issues and optimization of system performance but also contributes to the extension of infrastructure lifespan. By transitioning from theoretical exploration to practical application, this section underscores the study's narrative, bridging the gap between cutting-edge technology and its application in enhancing sustainability, efficiency, and occupant comfort within built environments.

Research Gap

While the potential of Digital Twin technology and IoT sensors to revolutionize building maintenance is widely recognized, empirical studies that detail their application in real-world construction projects are notably lacking. This is especially true for studies focusing on the optimization of HVAC systems within educational environments. This existing gap in the literature highlights a disconnect between theoretical advancements and their practical applications, underscoring the need for empirical research that demonstrates the real-world efficacy of these technologies. This study seeks to bridge this gap by providing an in-depth analysis of the Papa Giovanni XXIII school case. Through this analysis, it contributes valuable insights into the discourse on smart building technologies, advocating for the development of more efficient, sustainable, and occupant-centered built environments.

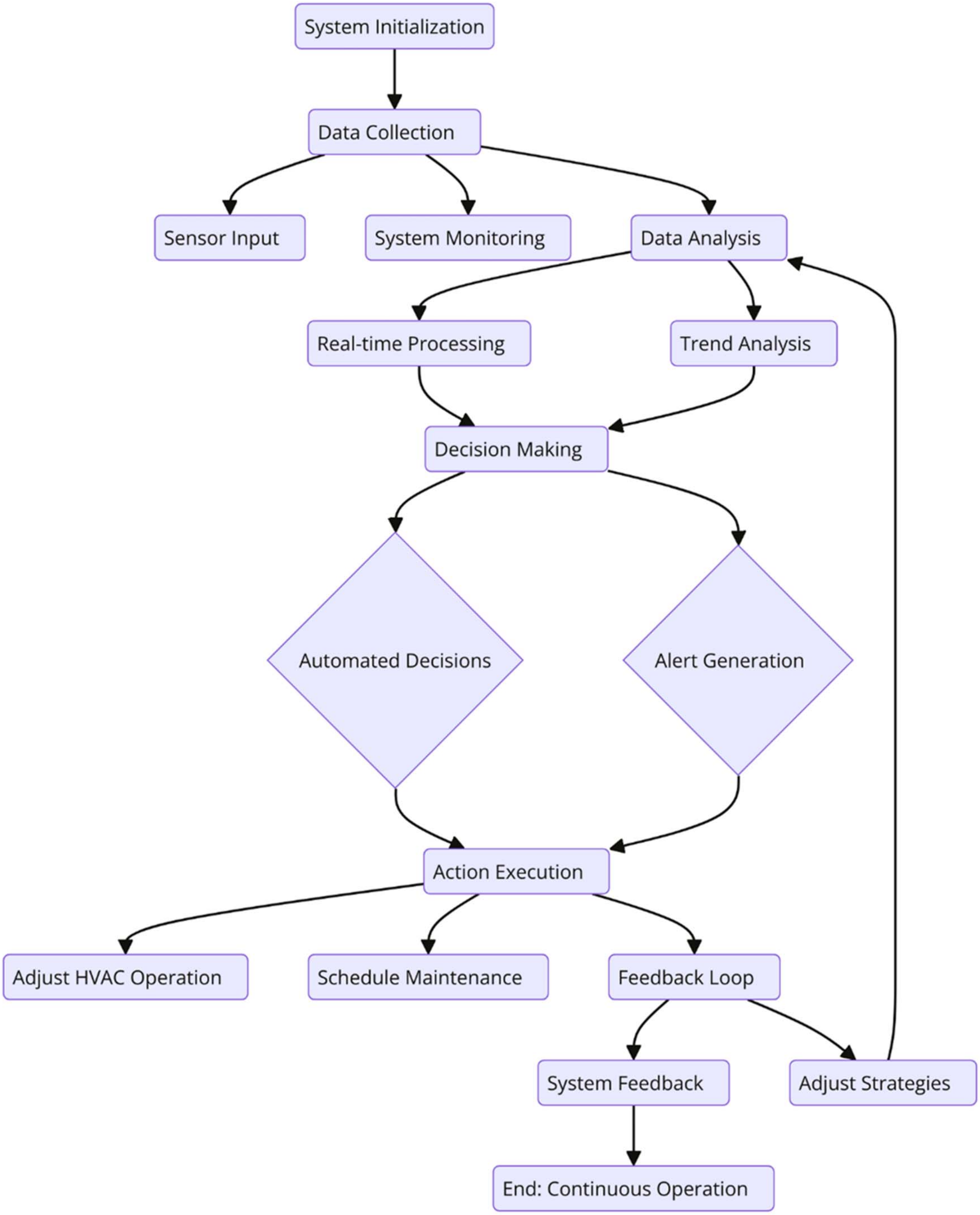

Fig. 1. Flowchart of control strategies.

Methodology

To illustrate the advanced control strategies employed in the system, a flowchart (Fig. 1) that outlines the decision-making processes and interactions among the digital model, IoT sensors, and control mechanisms is incorporated. This flowchart provides a visual representation of how data are processed and utilized to optimize system performance through predictive maintenance strategies.

Study Design

This research adopts a case study methodology to investigate the implementation of Digital Twin technology and IoT sensors for predictive maintenance, specifically targeting HVAC systems in educational settings. This methodological approach is chosen for its ability to provide nuanced insights into the intricate relationships among innovative technology, system performance, and strategic maintenance within the authentic context of a school environment.

The Papa Giovanni XXIII school in Nichelino, Italy, was selected as the case study location based on several criteria: its recent incorporation of advanced HVAC systems, its commitment to fostering an optimal learning environment, and its geographical location in Climate zone E, which is characterized by specific heating demands. These factors collectively presented a distinctive opportunity to scrutinize HVAC system performance during critical heating periods, crucial for maintaining conducive indoor conditions.

In selecting IoT sensors for the study, considerations were made for accuracy, low energy consumption, seamless connectivity options (including Wi-Fi and Bluetooth), and compatibility with the school's existing HVAC infrastructure. This careful selection ensured that the installation process caused minimal disruption and that data collection was efficient and effective.

Key performance indicators (KPIs) such as energy consumption, temperature consistency, and airflow rates were identified as critical measures of system efficiency. These KPIs were systematically measured and analyzed to evaluate and enhance the HVAC system's performance throughout the study's predictive maintenance process.

The primary objective of this case study is to assess the impact of integrating Digital Twin technology and IoT sensors on optimizing HVAC system maintenance. Expected outcomes include demonstrating real-time KPI monitoring through Digital Twin technology and evaluating the role of a predictive maintenance strategy in enhancing system reliability, reducing downtime, and improving energy efficiency.

The investigation covered the heating season from late October to early April 2023, a period strategically chosen to capture the operational dynamics of the HVAC system under peak demand. This time frame was critical for understanding the system's maintenance requirements and identifying performance challenges, providing essential insights for the study's objectives.

Digital Twin Implementation

Numerical Models in the Digital Twin

The implementation of the Digital Twin at the Papa Giovanni XXIII school involves the use of several advanced numerical models to simulate and predict the performance of the HVAC system. These models are critical for processing the data collected from IoT sensors and enabling predictive maintenance.

Thermodynamic models play a central role in simulating the heat transfer processes within the HVAC system. These models take into account various physical parameters such as temperature, humidity, air velocity, and heat flux. By applying the principles of thermodynamics, these models predict how heat is absorbed, stored, and released within the system's components, including heat exchangers, ducts, and indoor spaces. Analyzing the thermal dynamics allows for the identification of inefficiencies in heat exchange processes, helping to optimize heating and cooling cycles. For instance, if the thermodynamic model detects consistent overcooling in a specific zone, it can adjust the system's operation to prevent energy wastage, while maintaining comfort.

Another crucial component is the computational fluid dynamics (CFD) models, which simulate the airflow patterns within the HVAC ductwork and the spaces served by the system. These models consider factors such as airflow rate, pressure drops, turbulence, and the physical layout of the ductwork and rooms. CFD models provide detailed insights into airflow distribution, enabling the identification of potential blockages, leaks, or imbalances. This information is essential for ensuring uniform temperature distribution and adequate ventilation throughout the building. For example, if the CFD model reveals reduced airflow in a particular duct, maintenance can be scheduled to inspect and clear any obstructions, thus improving system efficiency and indoor air quality.

Predictive maintenance models are integral to the Digital Twin implementation. These models use machine learning algorithms to analyze historical and real-time data from IoT sensors. Techniques such as regression analysis, neural networks, and anomaly detection algorithms are employed to identify patterns indicative of potential system failures. By analyzing data trends and detecting anomalies, predictive maintenance models generate alerts for maintenance needs before failures occur. For instance, if an unusual vibration pattern is detected in a fan, the predictive maintenance model can trigger an alert to inspect and repair the fan before it fails, thereby preventing unplanned downtime and extending the system's lifespan.

Energy consumption models are utilized to predict the HVAC system's energy usage based on operational parameters and external conditions. These models incorporate historical energy usage data, real-time sensor inputs, and factors such as occupancy patterns, weather conditions, and system load. By monitoring and optimizing energy usage, these models identify periods of high consumption and potential energy-saving opportunities. They help implement strategies like demand response, wherein the system reduces energy consumption during peak demand periods without compromising comfort. For instance, if the energy consumption model predicts a spike in energy usage due to an upcoming heatwave, it can preemptively adjust the system's operation to mitigate the impact on energy bills.

Table 1 provides an overview of the essential parameters for each model, offering insight into the data inputs that drive the simulations. Table 2 summarizes the impact of predictive maintenance on system performance, showing how early interventions have improved reliability and efficiency.

Implementation Process and Challenges

Autodesk's Tandem was selected as the foundational software for developing the school's HVAC system Digital Twin. This choice was driven by Tandem's robust capabilities for seamless integration with BIM data, its user-friendly interface for assimilating IoT data, and its analytical prowess. Particularly, Tandem's ability to visually represent operational data played a crucial role in deepening the

Table 1. Key parameters in numerical models

Model	Key parameters	Description
Thermodynamic model	Temperature, humidity, heat flux	Simulates heat transfer processes
CFD model	Airflow rate, pressure, turbulence	Analyzes airflow patterns within the HVAC ductwork
Predictive maintenance model	Vibration, noise levels, operating time	Detects anomalies indicative of potential failures
Energy consumption model	Historical energy data, real-time sensor inputs	Predicts and optimizes energy usage

Table 2. Summary of predictive maintenance outcomes

Date	Issue detected	Action taken
January 15, 2023	High vibration	Fan inspection
February 10, 2023	Reduced airflow	Duct cleaning
March 5, 2023	High energy usage	System optimization

understanding of the HVAC system's performance, thereby facilitating a more informed approach to maintenance decision-making.

The project encountered significant hurdles related to sensor integration and data synchronization, particularly with existing sensors not initially compatible with the Digital Twin framework. Through the development of custom adapters and the implementation of enhanced data algorithms, the project team successfully achieved accurate synchronization between real-time sensor data and the Digital Twin model, ensuring the reliability and integrity of the system's data feed.

Recognizing the critical importance of safeguarding sensitive information within an educational setting, the project implemented robust measures including end-to-end encryption for data transmission and stringent access controls. These measures were meticulously designed to protect the privacy and security of collected data, adhering to the highest standards of data protection.

Strategic placement of IoT sensors within the HVAC ductwork was critical to capturing essential data points indicative of system health, such as airflow rate, temperature, and velocity. This strategic sensor placement was informed by a thorough analysis of the HVAC system's layout, ensuring that data collection points were optimally located to provide valuable insights into system performance.

The mapping of real-time sensor data onto the Digital Twin model in Tandem enabled a dynamic visualization of the HVAC system's condition. To process these data, advanced analytics and machine learning algorithms were employed, utilizing sophisticated techniques to identify deviations from performance baselines. These deviations were analyzed as potential indicators of maintenance needs, guiding the predictive maintenance strategy.

The overarching goal of this Digital Twin deployment was to establish a predictive maintenance framework that could preemptively identify potential system failures and optimize maintenance schedules. This strategic framework aimed to reduce downtime, improve energy efficiency, and extend the lifespan of HVAC components by adopting a proactive and data-driven approach to maintenance.

Predictive Maintenance Strategy

The adoption of a predictive maintenance model for the HVAC system at the Papa Giovanni XXIII school signifies a strategic departure from traditional, reactive maintenance approaches. This new model, powered by the synergistic use of Digital Twin technology and IoT insights, focuses on proactive measures to anticipate and resolve system issues before they escalate.

Establishing Baseline Performance Metrics

To establish initial baseline performance metrics, a two-pronged approach was employed: analyzing manufacturer specifications and historical system performance data. This foundational step was crucial in creating a benchmark against which real-time operational data could be compared, facilitating the early detection of anomalies.

Manufacturer specifications provide the ideal performance parameters for the HVAC system components. These specifications include data on optimal operating temperatures, airflow rates, energy consumption, pressure levels, and efficiency ratings.

For a particular HVAC unit, the manufacturer might specify:

1. Optimal operating temperature: 22°C
2. Airflow rate: 500 m^3/h
3. Energy consumption: 1.2 kW·h/h
4. Pressure level: 150 Pa
5. Efficiency rating: 85%

These parameters were used as reference points to determine the expected performance of the HVAC system under normal operating conditions.

Historical performance data were collected from the existing building management system (BMS) and IoT sensors previously installed in the HVAC system. These data included records of temperature, humidity, energy consumption, airflow rates, and system failures over a specified period.

Data collected over a 6-month period included:

1. Average operating temperature: 21.5°C
2. Average airflow rate: 480 m^3/h
3. Average energy consumption: 1.3 kW·h/h
4. Average pressure level: 145 Pa
5. Recorded system failures: two incidents of compressor failure

The first step involved gathering all relevant data from both manufacturer specifications and historical records. These data were then organized and cleaned to ensure accuracy and consistency.

The next step was to compare the historical data against the manufacturer specifications. This comparison helped identify deviations from the expected performance. For instance, if the average energy consumption recorded was higher than the manufacturer's specified value, it indicated potential inefficiencies.

Statistical methods were applied to analyze the historical data. Techniques such as mean, median, standard deviation, and regression analysis were used to understand the normal operating range and identify any outliers.

Using the insights from the comparative and statistical analyses, baseline performance metrics were established. These baselines represented the expected range of performance parameters under normal conditions (Table 3).

Machine Learning Models for Predictive Maintenance

The integration of machine learning models with the Digital Twin and IoT sensors is crucial for the predictive maintenance strategy. These models analyze historical and real-time data to predict potential system failures and optimize maintenance schedules. The

Table 3. Baseline benchmarks for real-time monitoring and anomaly detection

Parameter	Manufacturer specification	Historical data	Baseline metric
Operating temperature (°C)	22	21.5	21.5–22.5
Airflow rate (m^3/h)	500	480	470–510
Energy consumption (kW·h/h)	1.2	1.3	1.1–1.3
Pressure level (Pa)	150	145	140–160

machine learning models employed include regression analysis, neural networks, and anomaly detection algorithms.

Regression analysis helps predict future system performance based on historical data. This technique identifies trends and potential deviations from expected behavior, allowing for the detection of anomalies that may indicate maintenance needs. A regression model analyzes past data to predict energy consumption based on temperature and occupancy patterns. Deviations from the predicted energy usage can trigger maintenance alerts.

Neural networks are employed to analyze complex patterns in the operational data. These models are particularly effective in handling multivariate data and learning from diverse inputs. Neural networks iteratively improve their predictive accuracy by adjusting weights based on feedback from real-time data. A neural network model is trained on historical data to recognize normal operating patterns. If the model detects an unusual vibration pattern in a fan, it can predict potential failure and generate an alert.

Anomaly detection algorithms identify data points that deviate significantly from the established baselines. These algorithms are essential for detecting early signs of system degradation or failure. An anomaly detection algorithm monitors real-time sensor data for unusual temperature spikes or drops, signaling potential issues with the HVAC system.

Interaction with the Digital Twin and IoT Sensors

The Digital Twin acts as a dynamic representation of the HVAC system, integrating real-time data from IoT sensors with the predictive capabilities of machine learning models. Here is how the interaction works.

1. IoT sensors continuously collect data on parameters such as temperature, humidity, airflow rate, and energy consumption. These data are transmitted in real time to the Digital Twin platform, Autodesk Tandem, which assimilates and visualizes the information.
2. The Digital Twin provides a real-time view of the HVAC system's condition, allowing for continuous monitoring. Machine learning models analyze these real-time data, comparing it against the established baselines to detect anomalies. For example, real-time data from temperature sensors are fed into the neural network model, which evaluates the data against historical patterns. If an anomaly is detected, the model generates a predictive alert.
3. When the machine learning models identify deviations from normal operating conditions, predictive alerts are generated. These alerts inform the maintenance team of potential issues, enabling timely and precise interventions. The Digital Twin logs all maintenance actions, creating a comprehensive database for refining future maintenance strategies and predictive models. For instance, if the energy consumption model predicts an unusual increase in energy usage due to an upcoming heatwave, the system can preemptively adjust its operation to mitigate the impact, scheduling maintenance to ensure optimal performance.
4. The maintenance strategy is not static; it evolves through ongoing refinement. Adjustments to the machine learning models are informed by real-time system feedback, accommodating seasonal variations and other dynamic factors. This continuous learning process substantially improves maintenance prediction accuracy. For example, during winter, the system might experience different operational stresses compared with summer. The machine learning models adjust their predictions based on seasonal data, ensuring accurate maintenance scheduling year-round.

Detail on Data Analysis Techniques

The implementation of the Digital Twin for the school's HVAC system leverages a sophisticated array of data analysis tools and algorithms within Autodesk's Tandem platform. These tools transform raw sensor data into actionable insights, enabling predictive maintenance strategies that are both dynamic and effective. Two primary analytical techniques are utilized—regression analysis and neural networks.

Regression Analysis

Regression analysis is a statistical method used to predict system performance trends based on historical data. This technique helps identify potential deviations that may indicate maintenance needs. The specific type of regression analysis used can vary, but common approaches include linear regression, multiple regression, and polynomial regression.

Linear regression establishes a relationship between a dependent variable (e.g., energy consumption) and one or more independent variables (e.g., temperature, humidity). The model fits a linear equation to the observed data, enabling predictions based on the identified trend. To predict energy consumption, the model used the equation

$$E = \beta_0 + \beta_1 T + \beta_2 H + \varepsilon \tag{1}$$

where E = energy consumption; T = temperature; H = humidity; β_0 = intercept; β_1 and β_2 = coefficients; and ε = error term.

Multiple regression extends linear regression by incorporating multiple independent variables. This approach is particularly useful for understanding how various factors collectively influence system performance. The multiple regression model predicted energy consumption based on temperature, humidity, and occupancy levels

$$E = \beta_0 + \beta_1 T + \beta_2 H + \beta_3 O + \varepsilon \tag{2}$$

where O = occupancy levels.

Polynomial regression models the relationship between dependent and independent variables as an nth-degree polynomial. This is useful for capturing nonlinear relationships in the data. To model a nonlinear relationship, the polynomial regression used the equation

$$E = \beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3 + \varepsilon \tag{3}$$

The regression models are trained using historical performance data, including temperature, humidity, energy consumption, and system load. The training process involves fitting the model to the data to minimize the error term ε. Once trained, the models are validated using techniques such as k-fold cross-validation, where the data are divided into k subsets, and the model is trained and tested k times, each time using a different subset as the validation set. This ensures the model's robustness and reliability.

Neural Networks

Neural networks are computational models inspired by the human brain's structure and function. They are particularly effective in analyzing complex patterns in operational data. Neural networks consist of layers of interconnected nodes (neurons), each performing a simple computation. These models learn iteratively to improve predictive accuracy over time.

A typical neural network architecture includes an input layer, one or more hidden layers, and an output layer. Each layer consists of multiple neurons connected by weighted edges.

1. Input layer: Receives raw sensor data (e.g., temperature, humidity, airflow rate).

2. Hidden layers: Perform computations to identify patterns and relationships in the data.
3. Output layer: Generates predictions (e.g., likelihood of system failure, maintenance timing).

The neural network is trained using a large data set comprising historical maintenance records and real-time performance data. The training process involves adjusting the weights of the connections between neurons to minimize the prediction error. This is typically done using backpropagation, an algorithm that calculates the gradient of the loss function and updates the weights accordingly.

Example training process:

1. Input data are passed through the network, and the output is computed.
2. The difference between the predicted output and the actual value is calculated using a loss function (e.g., mean-squared error).
3. The gradients of the loss function with respect to the weights are computed and used to update the weights, minimizing the error in subsequent iterations.

The neural network's performance is validated using techniques such as *k*-fold cross-validation and testing on unseen data. The model's ability to generalize to new data is crucial for accurate predictions. Additionally, the neural network is continuously adapted based on real-time system feedback, allowing it to accommodate seasonal variations and other dynamic factors.

For example, during winter, the HVAC system might experience different operational stresses compared with summer. The neural network model adjusts its predictions based on the seasonal data, ensuring accurate maintenance scheduling year-round.

Case Study: Implementing Digital Twin Technology in HVAC Systems at Papa Giovanni XXIII School

Implementation Overview

Implementing Digital Twin technology in the HVAC system of the Papa Giovanni XXIII school in Nichelino, Italy, exemplifies a groundbreaking approach to predictive maintenance. This project was meticulously planned and executed to demonstrate the practical benefits of Digital Twin technology in enhancing maintenance strategies within educational institutions and beyond (Fig. 2). A detailed examination of the school's HVAC system was conducted to gain insights into its design, components, and existing operational challenges. This crucial step identified optimal locations for IoT sensor placement, ensuring the collection of precise data for the functional development of the Digital Twin model.

Early engagement with key stakeholders, including school administrators and technical staff, was pivotal. These discussions ensured alignment on the project's goals and outcomes, securing essential support and facilitating a shared understanding of the anticipated impact on the school's daily operations.

School Building Description

The Papa Giovanni XXIII school is located in Nichelino, Italy, and serves as an educational facility for Grade K-12. The building spans an area of approximately 10,000 m^2 and consists of multiple sections, including classrooms, laboratories, administrative offices, and communal areas such as a gymnasium and auditorium.

The school building is oriented north–south, maximizing natural light in key learning areas, while minimizing solar heat gain, which is critical for energy efficiency. The structure is primarily constructed of reinforced concrete with large, double-glazed windows that provide adequate insulation and soundproofing.

The building envelopes are designed with thermal insulation properties that comply with current energy efficiency regulations. External walls are equipped with weather-resistant finishes to withstand the local climatic conditions, which include cold winters and warm summers.

The HVAC system implemented at the Papa Giovanni XXIII school is a centralized system designed to provide optimal thermal comfort and air quality across all seasons. It includes the following:

1. Gas-fired boilers supply heat via radiators installed in all rooms, with automatic controls to adjust the temperature based on real-time sensor data.
2. Centralized air-conditioning units are equipped with eco-friendly refrigerants and advanced filtration systems to ensure clean air circulation.
3. CO_2 sensors control the mechanical ventilation system, which adjusts the fresh air supply based on the occupancy and specific activities in different school zones.

Description of Sensor Mapping

The implementation of IoT sensors within the HVAC system of the Papa Giovanni XXIII school was strategically designed to optimize the monitoring and control of environmental parameters critical to maintaining an efficient and effective learning environment. The following describes the placement and purpose of each sensor type within the system, as depicted in Fig. 3.

Air flow detection sensors are strategically placed at key points in both the delivery and the return ducts of the HVAC system. These sensors are critical for monitoring the rate and consistency of air flow throughout the building. By capturing real-time data on air movement, these sensors help in assessing system efficiency and detecting anomalies in air distribution that could indicate blockages or leaks.

The locations were selected as follows:

1. Entry and exit points of the main delivery ducts.
2. Junctions where ducts split to service different building zones.
3. Near the HVAC system output in areas such as the main assembly hall and classrooms, ensuring coverage across varied usage scenarios.

Temperature sensors are installed at various locations to monitor the ambient temperature of different school zones. These sensors provide continuous feedback on the thermal conditions, enabling the HVAC system to adjust heating or cooling output dynamically for optimal comfort and energy efficiency.

The locations were selected as follows:

1. Classrooms, laboratories, and administrative offices to ensure comfort conducive to the activities in these areas.
2. Near external exits and windows to gauge the effect of external temperature changes on the indoor environment.
3. In proximity to the HVAC central unit to monitor the temperature of air being circulated.

The data collected by these sensors are integrated into the school's BMS, in which advanced control strategies are applied. The BMS uses these data to execute several key functions.

1. Based on the input from air flow and temperature sensors, the HVAC system can alter fan speeds and damper positions to modify air flow rates and adjust heating or cooling intensity almost instantaneously.
2. Sensor data help predict potential system failures or identify maintenance needs before they become critical, reducing downtime and repair costs.
3. By analyzing trends from the sensor data, the BMS optimizes the HVAC operations to minimize energy consumption, while maintaining comfort, contributing to the school's sustainability goals.

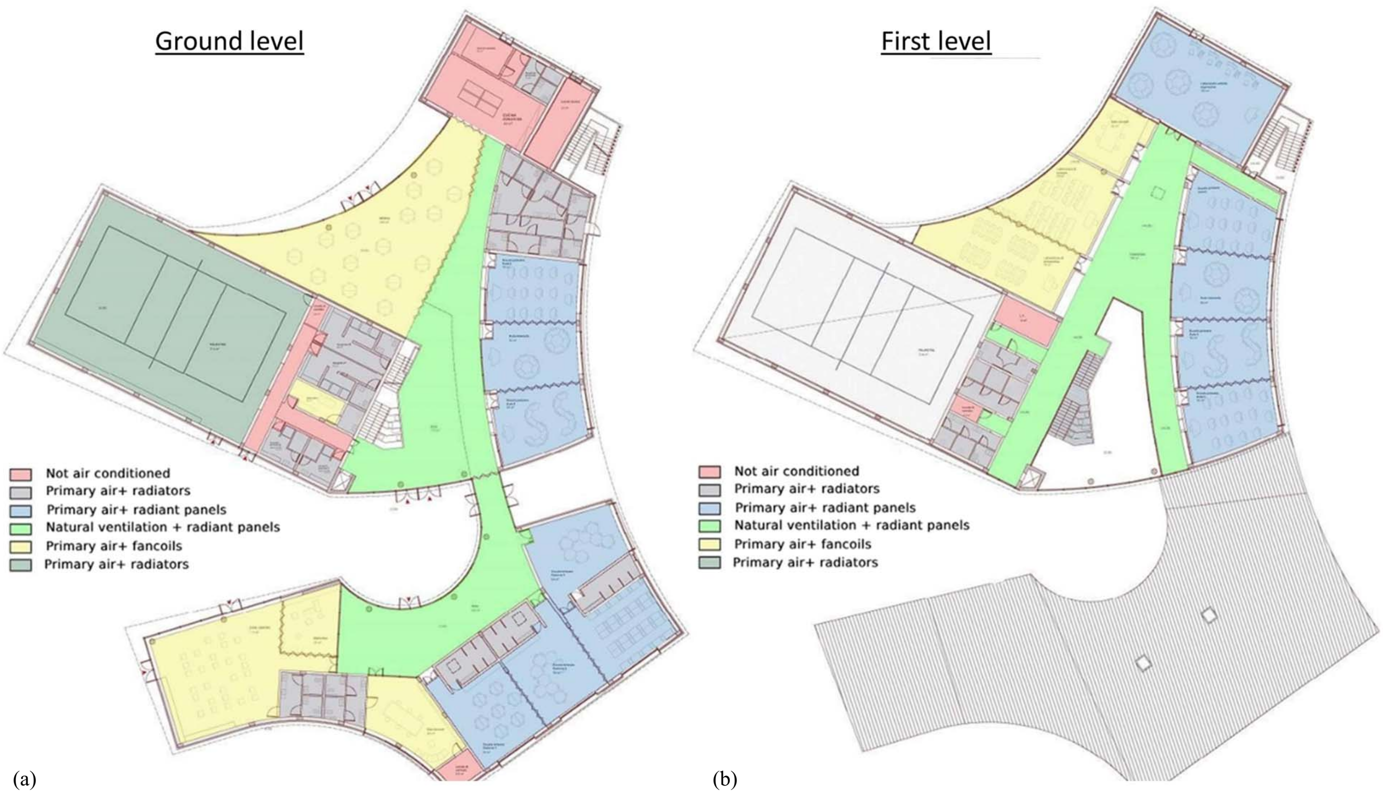

Fig. 2. (a) Ground floor; and (b) first floor of the Papa Giovanni XXIII school in Nichelino.

In this research, specific IoT sensors to monitor environmental conditions and airflow within the HVAC system of the Papa Giovanni XXIII school cafeteria in Nichelino (TO) was employed. To achieve precision and reliability in the measurements, the RTD PT100 sensor for temperature detection and the Honeywell 26PC Series differential pressure sensor for airflow measurement was selected.

The RTD PT100 sensor, a Resistance Temperature Detector, is renowned for its high accuracy and long-term stability. This sensor exhibits a resistance of 100 Ω at 0°C and operates over a temperature range of −200°C to +850°C. It maintains a tolerance of ±0.15°C at 0°C, conforming to IEC 60751 standards. With a maximum annual drift of just 0.04°C, PT100 is particularly suited for precision temperature monitoring in HVAC applications, ensuring effective thermal regulation within a cafeteria environment.

The Honeywell 26PC Series differential pressure sensor to measure the airflow by detecting pressure differences across air duct restrictions was utilized. This sensor offers a measurement range from 0–1.0 in H_2O to 0–10 in H_2O (0–0.25 to 0–2.5 kPa) and delivers outputs with an accuracy of ±0.25% of the full scale. Its output varies from 0.5 to 4.5 V, making it highly reliable for accurate airflow assessments within the HVAC system ducts.

The RTD PT100 sensors were strategically positioned at critical locations within the school's cafeteria to continuously monitor temperature and humidity. Similarly, the Honeywell 26PC Series sensors were installed in the air ducts to provide precise airflow data. This strategic placement ensures comprehensive monitoring of the HVAC system's performance, facilitating optimal environmental comfort and system efficiency.

These sensors not only enable continuous monitoring but also enhance the capability to dynamically adjust the HVAC operations based on real-time data, thereby maintaining an ideal learning environment.

Integration of Autodesk's Tandem with BIM and IoT Data

Autodesk's Tandem was chosen for its superior ability to integrate with BIM data and offer intuitive interfaces for IoT data assimilation. The integration process involved several key steps:

1. The first step in the integration process was importing the existing BIM data of the school's HVAC system into Autodesk Tandem. These BIM data included detailed information on the physical and functional characteristics of the HVAC components, such as ductwork layouts, equipment specifications, and spatial configurations.
2. Next, a comprehensive network of IoT sensors was deployed throughout the HVAC ductwork, targeting critical areas to monitor vital parameters such as airflow rate, temperature, and velocity. Each IoT sensor was mapped to its corresponding BIM element within the Tandem platform. This mapping process involved associating sensor data points with specific components in the BIM model, enabling real-time monitoring and data visualization. For example, a temperature sensor installed in a specific duct segment was linked to the corresponding duct element in the BIM model, allowing for real-time temperature data to be visualized within the Digital Twin environment, providing insights into the thermal performance of that duct segment.
3. To ensure seamless data integration, custom adapters and data synchronization algorithms were developed. These tools facilitated the accurate and timely transfer of real-time sensor data into the Tandem platform. The data integration process involved setting up secure data transmission channels, using end-to-end encryption to protect data integrity and confidentiality. For

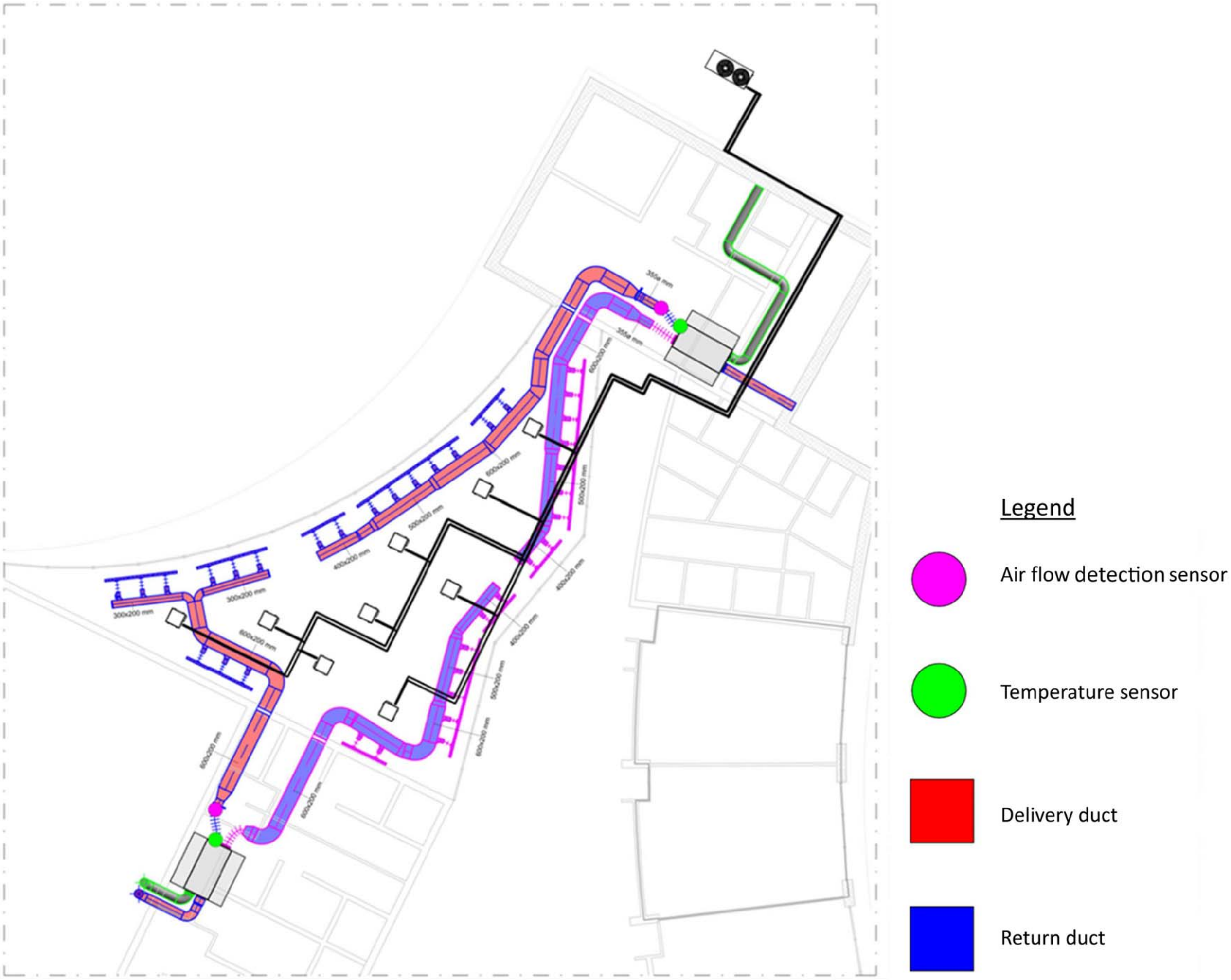

Fig. 3. Sensor placement map.

instance, real-time data from airflow sensors was continuously transmitted to the Tandem platform, where it was synchronized with the BIM model to reflect the current airflow conditions in the HVAC system.

4. With the BIM data and IoT sensor data integrated into Autodesk Tandem, the platform provided a dynamic visualization of the HVAC system's live status. Facility managers could interact with the Digital Twin, accessing real-time data and historical performance metrics to gain a comprehensive understanding of the system's condition.

Advanced Analytical Tools and Machine Learning Algorithms

Utilizing advanced analytical tools and machine learning algorithms, the Digital Twin system identified deviations from performance benchmarks, signaling maintenance needs. The specific tools and algorithms used included the following:

1. Statistical analysis tools were used to analyze historical performance data and establish baseline metrics. Techniques such as mean, median, standard deviation, and regression analysis helped identify normal operating ranges and detect anomalies. Autodesk Tandem's visualization capabilities allowed for real-time data representation, making it easier to monitor system performance and identify issues visually. For example, a time series graph of temperature data could highlight periods where the temperature deviated from the established baseline, signaling potential issues in the HVAC system.
2. Regression models predicted system performance trends based on historical data. Linear regression, multiple regression, and polynomial regression were used to understand the relationships between different variables and predict future performance.
3. Neural networks analyzed complex patterns in the operational data. The neural network architecture included an input layer, hidden layers, and an output layer. These models learned iteratively to improve predictive accuracy over time.
4. Anomaly detection algorithms identified data points that deviated significantly from the established baselines. These algorithms were essential for detecting early signs of system degradation or failure.

These models were trained and validated using historical data, employing techniques such as *k*-fold cross-validation to ensure their robustness and reliability. The continuous feedback from real-time data allowed the models to adapt to changing conditions, improving their predictive accuracy over time.

Fig. 4 shows a comparison between actual and predicted energy consumption over a period of time. The shaded areas highlight periods of significant deviations where the predicted values

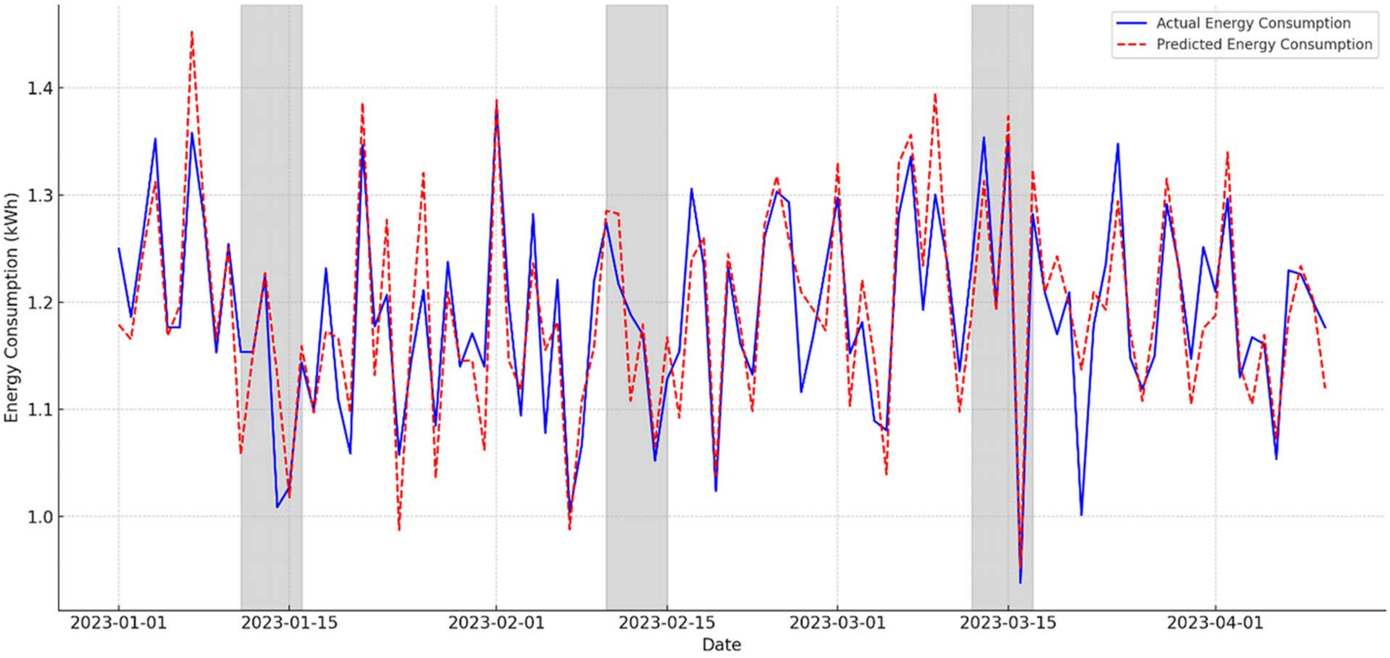

Fig. 4. Regression model output: Energy consumption prediction.

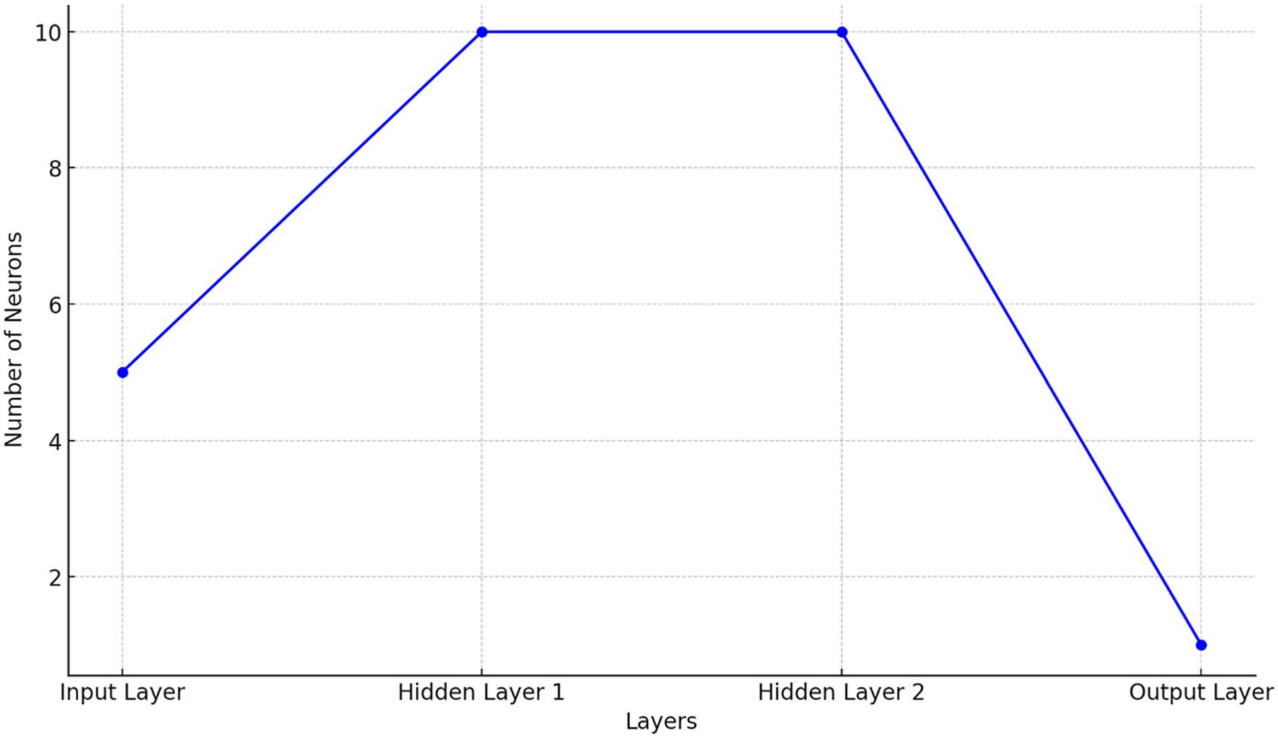

Fig. 5. Neural network architecture.

substantially differ from the actual values. This graph visually demonstrates the accuracy and predictive capabilities of the regression model used in the Digital Twin system.

Fig. 5 shows the layers of the neural network, including the input layer, two hidden layers, and the output layer. Each layer's number of neurons is indicated, highlighting the network's complexity. The time series graph compares the predicted maintenance needs (represented by a solid line) against the actual interventions (represented by a dashed line) over a 12-month period (Fig. 6). This graph illustrates how the neural network's predictions align with the real-world maintenance actions taken, demonstrating the model's effectiveness in predicting maintenance needs.

Maintenance Intervention and Outcomes

The introduction of a predictive maintenance strategy at the Papa Giovanni XXIII school, driven by Digital Twin technology and real-time data analytics, represents a significant leap forward in

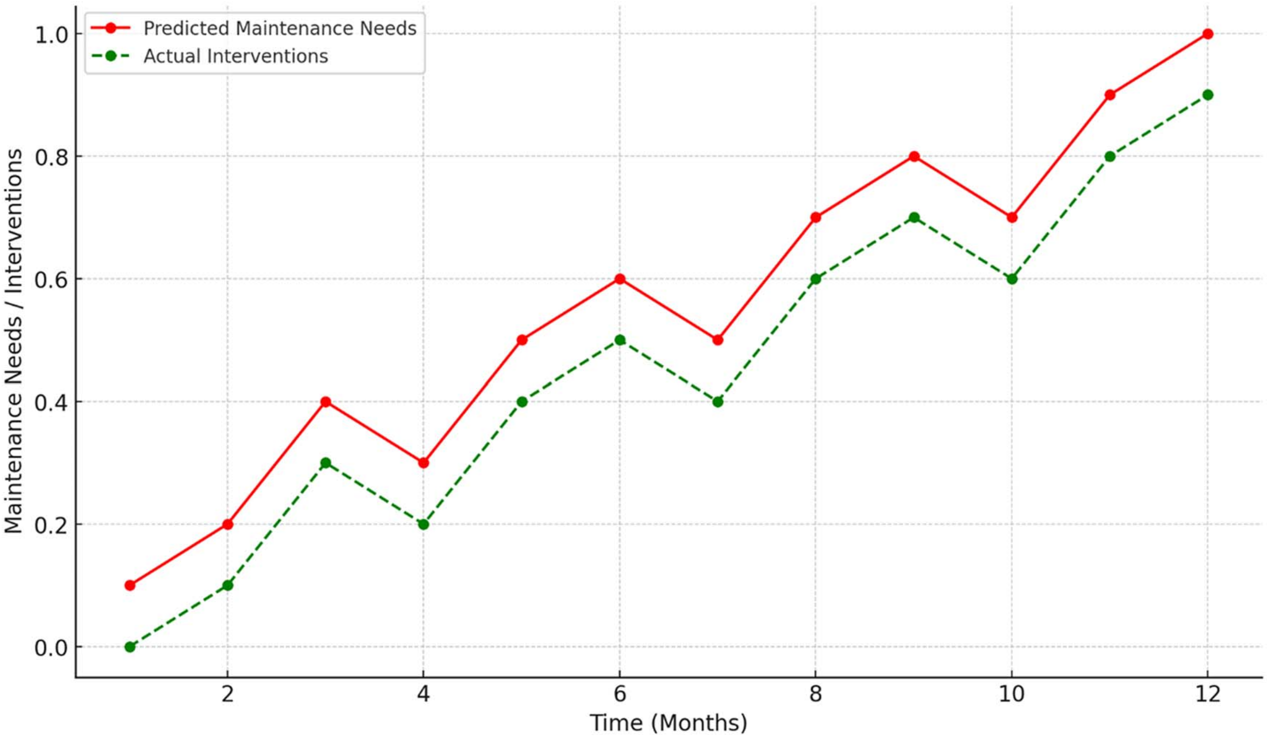

Fig. 6. Time series graph of predicted maintenance needs versus actual interventions.

the school's facility management practices. This shift to a proactive maintenance approach has markedly enhanced the HVAC system's reliability and operational efficiency.

The Digital Twin model played a crucial role in this transformation by generating predictive alerts that informed the facility management team of imminent system issues. This enabled them to perform preemptive maintenance, addressing problems before they could escalate. Documenting these interventions within the Digital Twin platform created a comprehensive historical data set, invaluable for refining future predictive models and strategies.

Following maintenance interventions, detailed evaluations were conducted to assess the restoration of the system's optimal operations. Continuous monitoring played a pivotal role in verifying the long-term effectiveness of the predictive maintenance strategy. This approach not only safeguarded a stable and comfortable indoor environment for the school community but also led to significant operational cost savings. By optimizing resource allocation and reducing system downtime, the school realized a more efficient use of its maintenance budget.

Fig. 7 displays the airflow measurements from sensors installed in the HVAC system before the maintenance intervention. The

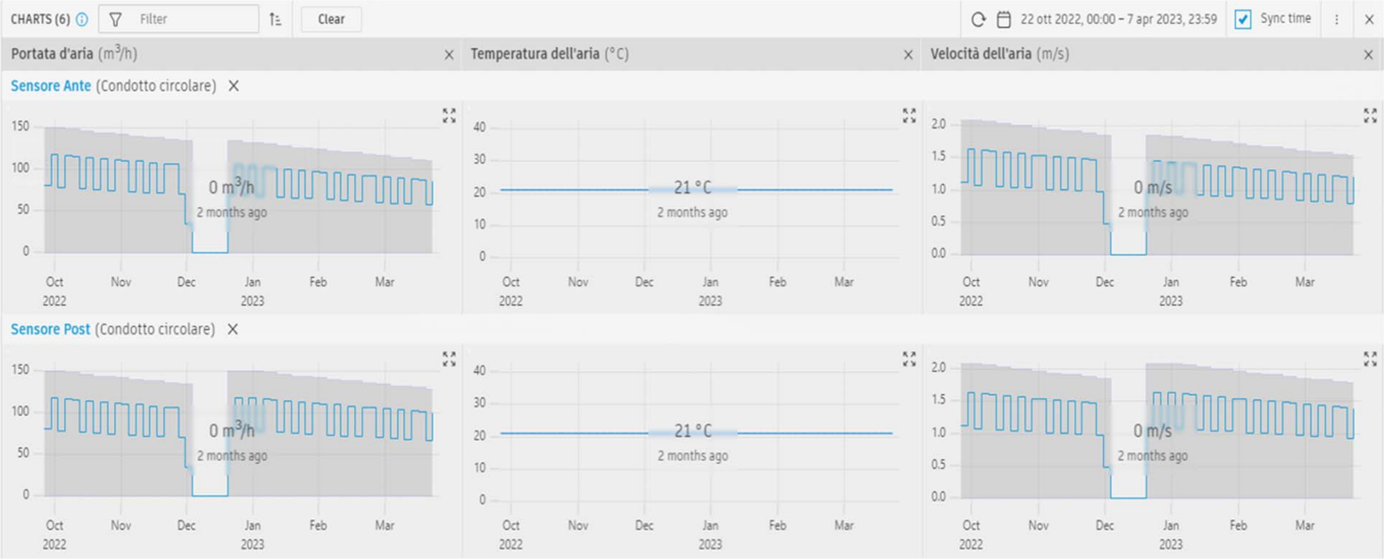

Fig. 7. Airflow data before maintenance.

Time: 2023-01-09 10:30:00 am Min: 134.00 Max: 134.00 Average [15m]: 134.00

Time: 2023-01-09 10:30:00 am Min: 150.00 Max: 150.00 Average [15m]: 150.00

Fig. 8. Airflow data after maintenance.

graph shows the airflow rate in cubic meters per hour (m³/h) over a 24-h period, demonstrating consistent performance with minimal fluctuations. The airflow rate is predominantly stable at 134.00 m³/h, indicating a steady state of operation. This baseline measurement serves as a reference point to assess the impact of maintenance activities on system performance.

Following maintenance interventions, Fig. 8 illustrates the airflow measurements to evaluate the effectiveness of the performed maintenance. Similar to the previous Fig. 7, it tracks airflow in cubic meters per hour over a 24-h period. Postmaintenance data reveal a consistent airflow rate of 150.00 m³/h, suggesting an improvement in system efficiency.

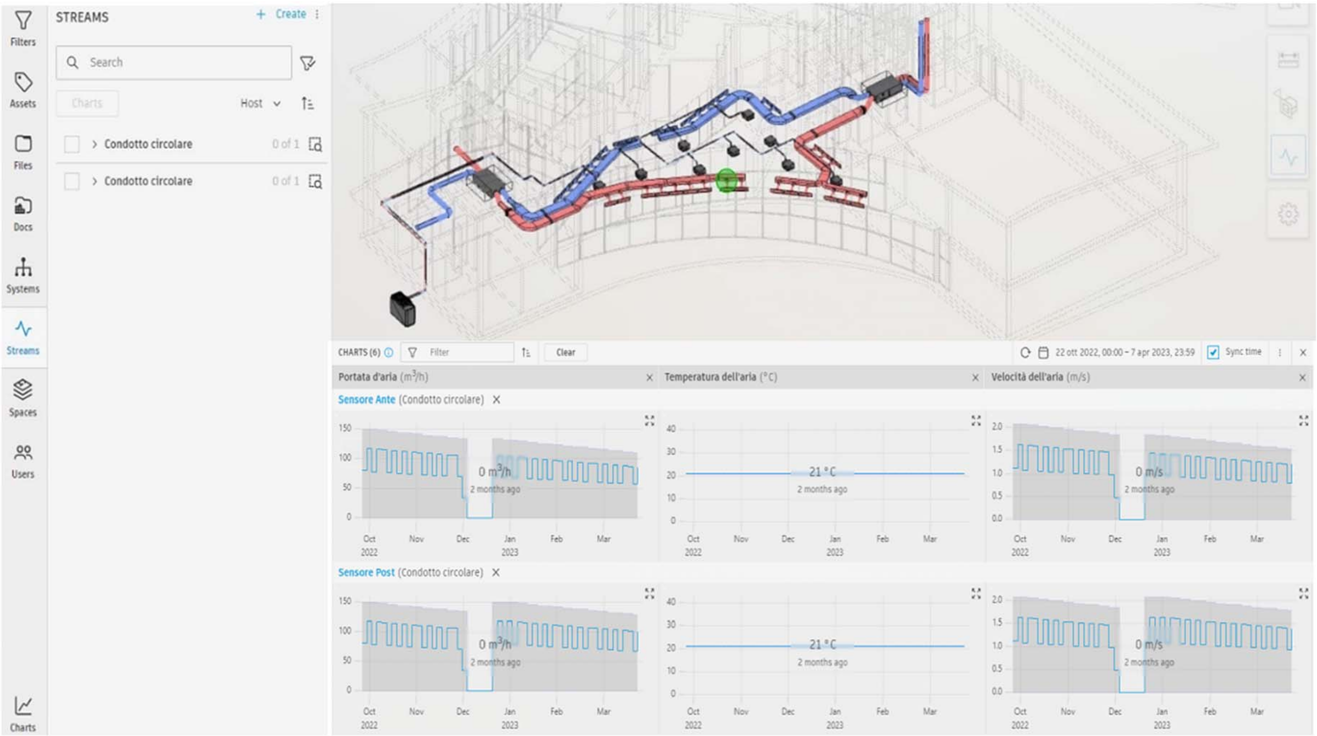

Fig. 9. Comparative airflow analysis.

Fig. 9 integrates the data from the previous two Figs. 7 and 8 offering a side-by-side comparison of airflow rates before and after maintenance. This comparative analysis is crucial for validating the impact of maintenance on HVAC performance. The graph underscores a clear improvement in airflow, supporting the effectiveness of the maintenance strategies employed.

The success of this predictive maintenance strategy highlights the evolving nature of building system management and the critical importance of incorporating innovative technologies and adopting a mindset geared toward continuous improvement. The Papa Giovanni XXIII school serves as an exemplary model within the educational sector, illustrating the profound impact that Digital Twin technology can have on enhancing the efficiency and reliability of building maintenance practices.

Through this case study, the transformative potential of leveraging Digital Twin technology for predictive maintenance in educational settings is clearly demonstrated. The school has set a benchmark in the sector, providing a compelling example of how embracing advanced technologies can lead to improved system reliability, enhanced comfort for building occupants, and operational cost savings.

Challenges and Solutions

The integration of Digital Twin technology and IoT sensors into the Papa Giovanni XXIII school's HVAC system presented several challenges, each necessitating innovative solutions and strategic planning to ensure the project's success. This initiative tested not only the technical capabilities but also the ability to collaborate effectively with all stakeholders.

The foremost challenge was the integration of IoT sensors into an HVAC system that was not initially designed to accommodate such technology. Through detailed compatibility assessments, the existing system's specifications against the operational requirements of various sensors were examined. This led to the identification of a need for custom adapters, designed and fabricated to enable seamless sensor integration without compromising the system's integrity or performance.

Solution implementation:

1. Conducted comprehensive evaluations of HVAC components and potential sensors, focusing on power requirements, data output formats, and physical dimensions.
2. Collaborated with engineering firms to design and manufacture custom adapters, bridging the gap between the sensors and the HVAC system's existing components.

Handling the massive influx of data from the IoT sensors posed a significant challenge due to the volume and variety of data generated. Optimizing cloud storage solutions and implementing advanced data compression techniques allowed us to manage the data efficiently, reducing storage costs and enhancing processing speed. A selective data analysis strategy was adopted to focus on the most relevant data points for predictive maintenance.

Solution implementation:

1. Utilized cloud computing platforms for scalable storage solutions and robust data management capabilities.
2. Applied state-of-the-art data compression algorithms to minimize data size without sacrificing essential information.
3. Developed algorithms to automatically identify and prioritize critical data points for predictive maintenance, ensuring optimal use of computational resources.

Overcoming resistance from stakeholders accustomed to traditional maintenance practices required a thoughtful approach. Interactive workshops and training sessions were organized to demonstrate the tangible benefits of Digital Twin technology and the predictive maintenance approach. These sessions, featuring hands-on demonstrations and real-time data visualization, allowed stakeholders to witness the potential for system optimization, efficiency gains, and cost savings first-hand.

Solution implementation:

1. Designed tailored sessions to explain the principles of Digital Twin technology and predictive maintenance, supplemented by case studies and live demonstrations.
2. Leveraged Tandem's visualization tools to present real-time data from the school's HVAC system, highlighting the insights gained and issues potentially avoided through predictive maintenance.

Through targeted strategies and a collaborative approach, the challenges of implementing Digital Twin technology were successfully navigated, laying a solid foundation for its continued development and refinement. This experience underscores the value of adaptability, detailed planning, and active engagement with stakeholders in adopting new technologies for building maintenance, providing valuable lessons for future projects.

Results and Discussion

Key Findings

The integration of Digital Twin technology with IoT sensors introduced transformative advancements in the maintenance strategies of the HVAC system at Papa Giovanni XXIII school, demonstrating significant improvements in system performance, operational efficiency, and occupant comfort.

The deployment of IoT sensors enabled detailed monitoring of critical HVAC parameters, facilitating the early detection of potential issues. This precision monitoring acted as an early warning system, allowing for preemptive maintenance measures that effectively mitigated system inefficiencies.

Strategic scheduling of maintenance interventions, especially during less-disruptive periods such as school holidays, significantly reduced operational disruptions and maintained a conducive learning environment. This approach optimized resource allocation and enhanced maintenance efficiency.

A notable decrease in unscheduled HVAC system downtime was observed, illustrating the benefits of transitioning from a reactive to a proactive maintenance strategy. This transition ensured the continuous operation of essential heating and cooling systems, extended the lifespan of HVAC components, and achieved considerable cost savings.

Insights from the Digital Twin model informed maintenance actions that maintained the HVAC system within optimal operational parameters, crucial for ensuring a stable and comfortable indoor climate. This directly benefited the learning atmosphere and potentially improved health outcomes by reducing the presence of allergens and pollutants.

Advanced statistical analysis techniques, including regression analysis and machine learning algorithms, dissected the vast data set collected by IoT sensors. Statistical tests validated the significant impact of the predictive maintenance strategy on operational efficiency and indoor environment quality with a high degree of confidence.

Graphical representations detailed the positive effects of maintenance interventions on system performance over time. A comparative evaluation of the HVAC system's performance before and after implementing Digital Twin technology and IoT sensor

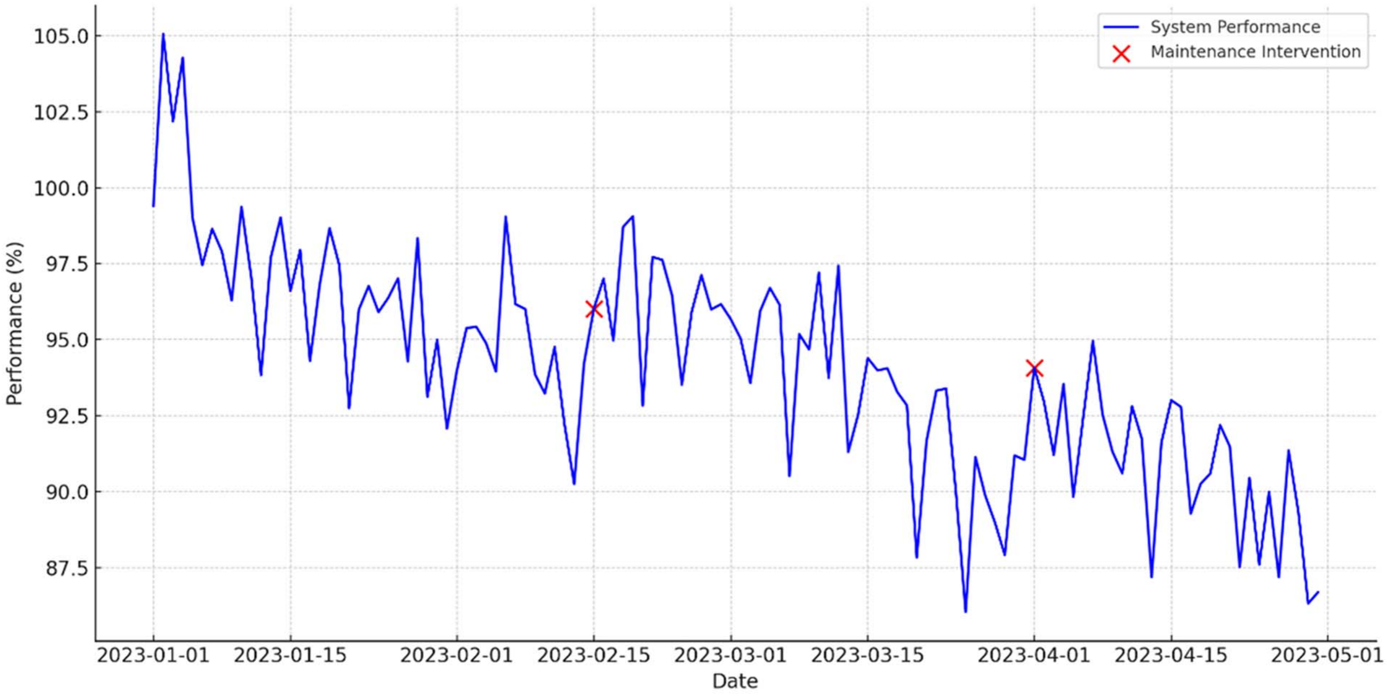

Fig. 10. HVAC system performance over time.

integration provided concrete evidence of the tangible benefits of predictive maintenance.

Fig. 10 illustrates the overall performance of the HVAC system at the Papa Giovanni XXIII school from January 1, 2023, to May 1, 2023. The line represents the aggregate system performance percentage, which is calculated based on key parameters such as temperature control, humidity levels, airflow rate, energy consumption, and pressure levels. The "X" marks indicate maintenance interventions, which are crucial in maintaining optimal system performance and preventing severe degradation.

Fig. 11 shows the temperature sensor readings (in °C) over the same period. The line indicates the temperature trend, while the "X" marks denote maintenance interventions. The steady increase in temperature reflects seasonal changes and the environmental

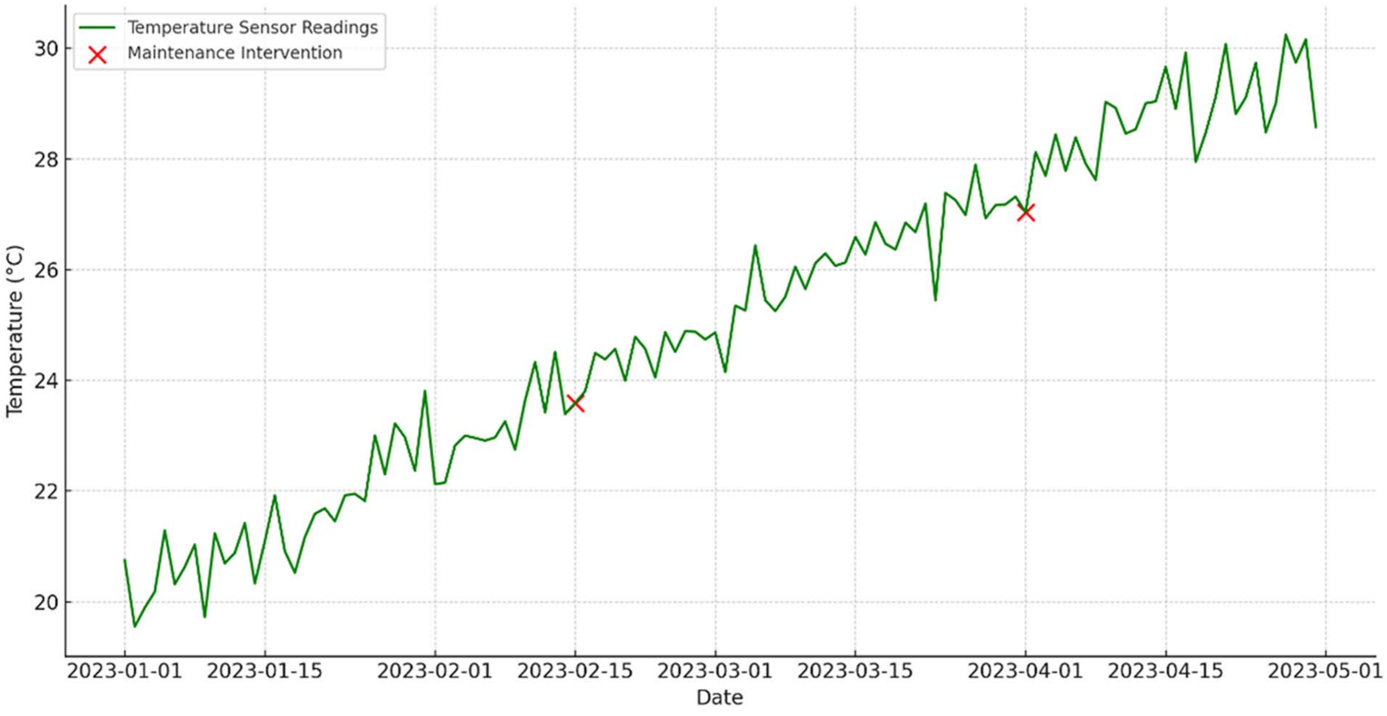

Fig. 11. Temperature sensor readings over time.

heat load, while the fluctuations and interventions demonstrate the HVAC system's efforts to maintain stable indoor conditions.

Comparative Analysis

A pivotal element of this study is the comparative evaluation of the HVAC system's performance at the Papa Giovanni XXIII school, both prior to and following the integration of Digital Twin technology and IoT sensors. This analysis, supported by graphical representations, not only showcases the tangible benefits of a predictive maintenance approach but also quantitatively assesses its impact on system reliability, efficiency, and the indoor environmental quality.

Initial analysis reveals a gradual performance decline in the HVAC system, characterized by decreasing efficiency and escalating operational strain. Such trends, indicative of wear and progressive system issues, pose risks of significant downtime or even catastrophic failure if left unaddressed.

The adoption of a predictive maintenance strategy, enriched by real-time IoT sensor data and Digital Twin analysis, marked a turning point. Subsequent maintenance interventions, informed by data-driven insights and optimally timed, not only arrested the system's performance decline but also initiated an upward trend in operational efficiency. This improvement signifies the restoration of the system to its optimal operational parameters, with marked reductions in energy consumption.

Two key graphical representations illustrate the strategy's efficacy. The first [Fig. 12(a)] charts the HVAC system's performance over several months, highlighting significant enhancements postintervention. The second [Fig. 12(b)] demonstrates the correlation between specific IoT sensor readings (e.g., temperature, airflow rates) and the timing of maintenance actions. These visualizations provide compelling evidence of the predictive maintenance strategy's success, showing how maintenance interventions are closely aligned with identified deviations in sensor readings, thereby affirming the effectiveness of this proactive approach.

The clear correlation between sensor data and maintenance timing not only ensures that interventions are both timely and targeted but also underscores the subsequent improvements in system performance. This validation supports the hypothesis that integrating IoT sensors with Digital Twin technology fosters a proactive maintenance model, thereby enhancing the system's reliability and extending its operational lifespan.

This comparative analysis highlights the considerable advantages of employing Digital Twin technology and IoT sensors within the maintenance strategies of HVAC systems in educational settings. By rigorously examining performance trends and sensor data correlations, the study corroborates the effectiveness of predictive maintenance, offering substantial contributions to the discourse on intelligent building management. These insights advocate for a shift toward data-driven, predictive maintenance strategies across the construction and facility management sectors, promising not only optimized operational efficiency and improved environmental conditions but also setting new standards for sustainability and occupant well-being in educational institutions.

Discussion

The implementation of Digital Twin technology and IoT sensors for predictive maintenance at the Papa Giovanni XXIII school represents a significant milestone in the field of architectural engineering. This study highlights a fundamental shift toward a proactive and data-driven approach to maintenance, underlining the pivotal role of technology in enhancing building management and decision-making processes.

The shift toward integrating these advanced digital tools into building management aligns with the broader trends in the industry, as highlighted by several key studies. For example, Bynum et al. (2013) and Issa et al. (2009) discussed the transformative impact of BIM on construction practices, which laid the foundation for more advanced applications like Digital Twins. The real-time dynamic representation provided by Digital Twin technology, as demonstrated in this study, extends the capabilities of BIM by enabling predictive maintenance strategies that proactively address system inefficiencies and failures (Mubarak et al. 2022).

Adopting predictive maintenance requires not only technological changes but also cultural and organizational shifts within institutions. Watson (2011) discussed the challenges and opportunities of digital buildings, emphasizing the need for specialized skills in data analysis

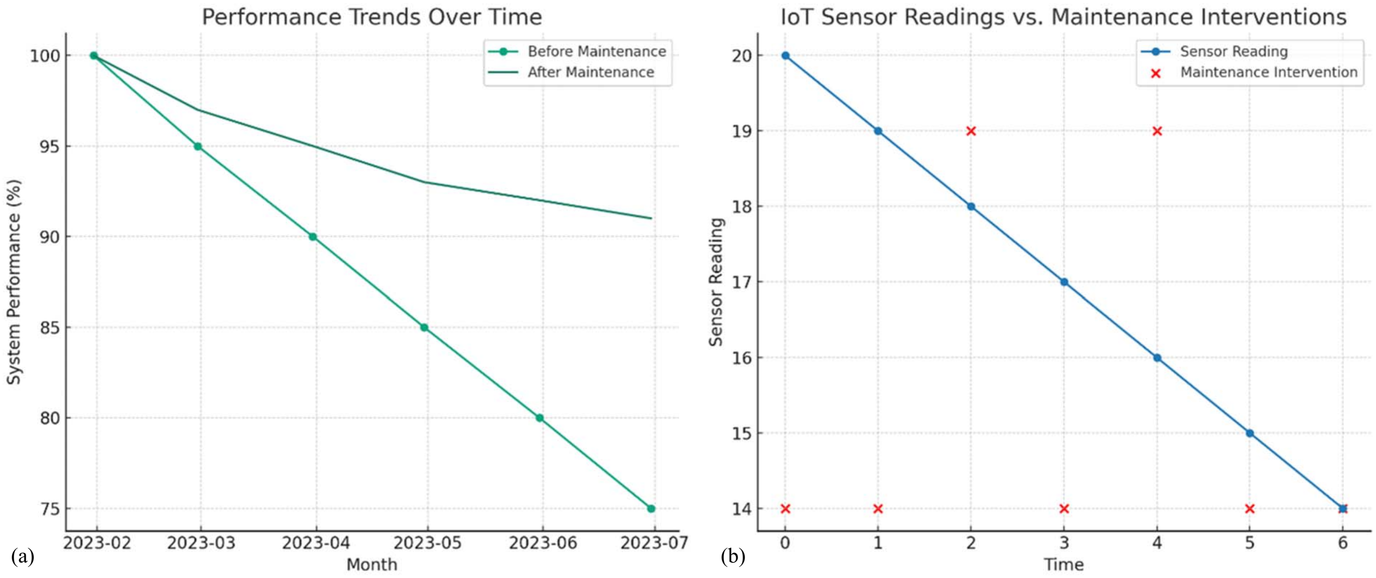

Fig. 12. (a) Performance trends over time; and (b) IoT sensor readings versus maintenance interventions.

and the complexity of technological integration. Despite these obstacles, the potential for improved building performance, sustainability, and operational efficiency presents compelling reasons for the industry to overcome these hurdles. This study's findings corroborated those of Yang et al. (2022), who highlighted the importance of overcoming initial investment challenges and technical complexities to realize the benefits of Digital Twin technology.

The integration of IoT sensors and advanced analytical tools significantly enhances the predictive capabilities of building management systems. Studies by Casini (2022) and Cheng et al. (2020) illustrated the impact of IoT in transforming building maintenance from reactive to proactive models. The deployment of a comprehensive network of IoT sensors within the school's HVAC system allowed for detailed monitoring and early detection of potential issues, which was consistent with the findings of Htet et al. (2023 and Tanasiev et al. (2022) on the role of IoT in optimizing building operations.

The proactive maintenance approach adopted in this study not only improved system reliability but also extended the operational lifespan of HVAC components. This aligned with the research of Calabrese et al. (2020 and Çınar et al. (2020), who emphasized the benefits of predictive maintenance in manufacturing and building systems. The reduction in unscheduled downtime and operational cost savings observed in this study further validated the effectiveness of predictive maintenance strategies, as discussed by Villa et al. (2021) and Opoku et al. (2023).

This study opens several avenues for further research.

1. Investigating how Digital Twin technology can enhance the energy efficiency of HVAC systems when integrated with renewable energy sources like solar or wind energy. This follows the suggestions of Silva and Araujo (2022) on integrating IoT with renewable energy sources.
2. Assessing the long-term effects of predictive maintenance on indoor air quality within educational settings through extensive monitoring and statistical analysis. This would build on the work of Long et al. (2023) on the impact of HVAC systems on indoor environmental quality.
3. Evaluating the effectiveness of predictive maintenance strategies in various climatic conditions to understand regional adaptations necessary for optimizing HVAC system performance. This could be informed by the findings of Parisio et al. (2014) and Calabrese et al. (2020).
4. Developing cost models to analyze the economic implications of implementing Digital Twin technology in HVAC maintenance, including the analysis of upfront investments, operational costs, and the financial benefits derived from system longevity and energy savings. This would extend the economic analyses presented by Agouzoul et al. (2023).

The successful application of these technologies at the Papa Giovanni XXIII school has broader implications, potentially influencing policy, setting new industry standards, and revolutionizing management practices across educational facilities worldwide. This underscores the necessity of integrating digital maintenance strategies into building codes and legislation to promote environments that are not only energy-efficient but also conducive to health and sustainability, as advocated by Rocha and Rodrigues (2017) and Egoavil et al. (2022).

This case study advocates for the widespread adoption of predictive, data-informed maintenance models across the construction and facility management sectors. Such models can spur innovation in sensor technology, analytics platforms, and integrated systems, aligning maintenance strategies with digital advancements to significantly impact resource allocation, policy formation, and the overall quality of indoor environments. Encouraging collaborations among educational institutions, technology providers, and government entities can foster the piloting of similar initiatives, promoting economies of scale, knowledge exchange, and further development of predictive maintenance technologies.

In summary, the adoption of Digital Twin technology and IoT sensors in the maintenance of educational facilities marks a transformative step toward more sophisticated, sustainable, and health-enhancing built environments. This research not only showcases the tangible benefits of such technologies but also charts a course for addressing challenges and harnessing their full potential, with the integration of artificial intelligence and Digital Twins heralding an even more promising future.

Conclusions

This research has illuminated the transformative impact of Digital Twin technology and IoT sensors on the predictive maintenance of HVAC systems in educational settings, with the Papa Giovanni XXIII school serving as a prime example. Key conclusions drawn from the study underscore the significant enhancements in system reliability, operational efficiency, and indoor environmental quality facilitated by these technologies. Specifically, the study found the following:

1. The application of Digital Twin technology, coupled with insights from IoT sensors, helped in the formulation of effective predictive maintenance strategies. This approach notably reduced unplanned downtimes and extended the lifespan of HVAC components, highlighting the advantages of a proactive maintenance model.
2. Maintenance interventions, informed by data-driven insights, led to operational improvements and cost savings. The study demonstrated how precise failure predictions and maintenance scheduling can optimize resource utilization, emphasizing the value of accuracy in maintenance planning.
3. The research stressed the importance of maintaining optimal HVAC system performance to ensure high-quality indoor environmental conditions, essential for conducive learning environments and positive health outcomes.

While the study's findings are compelling, its limitations—such as the focus on a single educational facility and the short-term observation period—highlight areas for future research. Proposed future studies should include the following:

1. Broadening the scope to include diverse educational facilities across various geographic and climatic conditions will enhance the understanding of the adaptability and scalability of predictive maintenance strategies.
2. Conducting long-term studies to assess the enduring impacts of predictive maintenance on system performance, energy efficiency, and cost implications will provide deeper insights into the sustained benefits of this approach.
3. Investigating the synergy between Digital Twin technology and renewable energy sources could offer further improvements in building sustainability and operational efficiency.

The study advocates for a broader integration of Digital Twin and IoT technologies across different building systems and into smart city frameworks, exploring their collective potential to improve urban infrastructure management.

To advance the adoption of these technologies in the construction and facility management sectors, it is recommended that stakeholders invest in professional training programs, allocate resources for technology acquisition and implementation, and foster partnerships to overcome adoption barriers and promote best practices.

The implementation of Digital Twin technology and IoT sensors marks a significant advancement in HVAC system management within educational facilities, laying a foundation for more efficient, sustainable, and health-supportive buildings. This study not only showcases the immediate benefits of these technologies but also opens avenues for further research and innovation, particularly in integrating artificial intelligence to enhance system management in the increasingly digital world.

Reflecting on the study's scope, there is a clear pathway for ongoing exploration that deepens the understanding of the potential of these technologies, fostering a culture of continuous improvement and rigorous evaluation within the architectural engineering field.

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

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References

Agouzoul, A., E. Simeu, and M. Tabaa. 2023. "Enhancement of building energy consumption using a digital twin based neural network model predictive control." In *Proc., Int. Conf. on Control, Automation and Diagnosis*, 1–6.

Aivaliotis, P., K. Georgoulias, and G. Chryssolouris. 2019. "The use of digital twin for predictive maintenance in manufacturing." *Int. J. Computer Integr. Manuf.* 32 (11): 1067–1080. https://doi.org/10.1080/0951192X.2019.1686173.

Boje, C., A. Guerriero, S. Kubicki, and Y. Rezgui. 2020. "Towards a semantic construction digital twin: Directions for future research." *Autom. Constr.* 114: 103179. https://doi.org/10.1016/j.autcon.2020.103179.

Bynum, P., R. R. A. Issa, and S. Olbina. 2013. "Building information modeling in support of sustainable design and construction." *J. Constr. Eng. Manage.* 139 (1): 24–34. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000560.

Calabrese, F., A. Regattieri, L. Botti, C. Mora, and F. G. Galizia. 2020. "Unsupervised fault detection and prediction of remaining useful life for online prognostic health management of mechanical systems." *Appl. Sci.* 10 (12): 4120. https://doi.org/10.3390/app10124120.

Cascone, S. 2023. "Digital technologies and sustainability assessment: A critical review on the integration methods between BIM and LEED." *Sustainability* 15 (6): 5548. https://doi.org/10.3390/su15065548.

Casini, M. 2022. "Extended reality for smart building operation and maintenance: A review." *Energies* 15 (10): 3785. https://doi.org/10.3390/en15103785.

Cheng, J. C. P., W. Chen, K. Chen, and Q. Wang. 2020. "Data-driven predictive maintenance planning framework for MEP components based on BIM and IoT using machine learning algorithms." *Autom. Constr.* 112: 103087. https://doi.org/10.1016/j.autcon.2020.103087.

Çınar, Z. M., A. Abdussalam Nuhu, Q. Zeeshan, O. Korhan, M. Asmael, and B. Safaei. 2020. "Machine learning in predictive maintenance towards sustainable smart manufacturing in industry 4.0." *Sustainability* 12 (19): 8211. https://doi.org/10.3390/su12198211.

Coupry, C., S. Noblecourt, P. Richard, D. Baudry, and D. Bigaud. 2021. "BIM-based digital twin and XR devices to improve maintenance procedures in smart buildings: A literature review." *Appl. Sci.* 11 (15): 6810. https://doi.org/10.3390/app11156810.

Di Gaetano, F., S. Cascone, and R. Caponetto. 2023. "Integrating BIM processes with LEED certification: A comprehensive framework for sustainable building design." *Buildings* 13 (10): 2642. https://doi.org/10.3390/buildings13102642.

Egoavil, X. P., F. S. Araujo, and J. De la Torre Salazar. 2022. "Viability of the digital twin in the inventory of educational assets to improve maintenance control." In *Proc., 2022 Congreso Int. de Innovación y Tendencias en Ingeniería*, 1–6. Bogotá, Colombia: CONIITI.

Fuller, A., Z. Fan, C. Day, and C. Barlow. 2020. "Digital twin: Enabling technologies, challenges and open research." *IEEE Access* 8: 108952–108971. https://doi.org/10.1109/ACCESS.2020.2998358.

Hannan, M. A., M. Faisal, P. J. Ker, L. H. Mun, K. Parvin, T. M. I. Mahlia, and F. Blaabjerg. 2018. "A review of internet of energy based building energy management systems: Issues and recommendations." *IEEE Access* 6: 38997–39014. https://doi.org/10.1109/ACCESS.2018.2852811.

Harkonen, K., L. Hannola, J. Lassila, and M. Luoranen. 2023. "Enhancing smartness and interoperability of building management systems in non-residential buildings." *Resourceedings* 3 (1): 64–74. https://doi.org/10.21625/resourceedings.v3i1.949.

Hosamo, H. H., and M. H. Hosamo. 2022. "Digital twin technology for bridge maintenance using 3D laser scanning: A review." *Adv. Civ. Eng.* 2022: 2194949. https://doi.org/10.1155/2022/2194949.

Hosamo, H. H., A. Imran, J. Cardenas-Cartagena, P. R. Svennevig, K. Svidt, and H. K. Nielsen. 2022. "A review of the digital twin technology in the AEC-FM industry." *Adv. Civ. Eng.* 2022: 2185170. https://doi.org/10.1155/2022/2185170.

Hou, L., S. Wu, G. (. Zhang, Y. Tan, and X. Wang. 2020. "Literature review of digital twins applications in construction workforce safety." *Appl. Sci.* 11 (1): 339. https://doi.org/10.3390/app11010339.

Htet, A., S. R. Liana, T. Aung, and A. Bhaumik. 2023. "Smart buildings in the age of internet technology: Civil engineering's role in shaping an energy-efficient future." *J. Technol. Innovations Energy* 2 (2): 8–19. https://doi.org/10.56556/jtie.v2i2.535.

Issa, R. R. A., P. C. Suermann, and S. Olbina. 2009. "Use of building information models in simulations." In *Proc., 2009 Winter Simulation Conf.*, 2664–2671. Austin, TX: WSC.

Khallaf, R., L. Khallaf, C. J. Anumba, and O. C. Madubuike. 2022. "Review of digital twins for constructed facilities." *Buildings* 12 (11): 2029. https://doi.org/10.3390/buildings12112029.

Kumar, A., S. Sharma, N. Goyal, A. Singh, X. Cheng, and P. Singh. 2021. "Secure and energy-efficient smart building architecture with emerging technology IoT." *Comput. Commun.* 176: 207–217. https://doi.org/10.1016/j.comcom.2021.06.003.

Lawal, K., and H. N. Rafsanjani. 2022. "Trends, benefits, risks, and challenges of IoT implementation in residential and commercial buildings." *Energy Built Environ* 3 (3): 251–266. https://doi.org/10.1016/j.enbenv.2021.01.009.

Lee, M. C., K. W. Mui, L. T. Wong, W. Y. Chan, E. W. M. Lee, and C. T. Cheung. 2012. "Student learning performance and indoor environmental quality (IEQ) in air-conditioned university teaching rooms." *Build. Environ.* 49: 238–244. https://doi.org/10.1016/j.buildenv.2011.10.001.

Long, H., J. Luo, Y. Zhang, S. Li, and X. Chen. 2023. "An intelligent long-term prediction model for indoor air quality based on informer." In *Proc., 2023 Int. Seminar on Computer Science and Engineering Technology*, 278–282. New York: Computer Science and Engineering Technology (SCSET).

Mi, S., Y. Feng, H. Zheng, Y. Wang, Y. Gao, and J. Tan. 2021. "Prediction maintenance integrated decision-making approach supported by digital twin-driven cooperative awareness and interconnection framework." *J. Manuf. Syst.* 58: 329–345. https://doi.org/10.1016/j.jmsy.2020.08.001.

Mubarak, A., M. Asmelash, A. Azhari, T. Alemu, F. Mulubrhan, and K. Saptaji. 2022. "Digital twin enabled industry 4.0 predictive maintenance under reliability-centred strategy." In *Proc., 2022 1st Int. Conf. Electrical, Electronics, Information and Communication Technologies*. Tiruchirappalli, India: ICEEICT.

Opoku, D.-G. J., S. Perera, R. Osei-Kyei, M. Rashidi, K. Bamdad, and T. Famakinwa. 2023. "Barriers to the adoption of digital twin in the construction industry: A literature review." *Informatics* 10 (1): 14. https://doi.org/10.3390/informatics10010014.

Parisio, A., D. Varagnolo, M. Molinari, G. Pattarello, L. Fabietti, and K. H. Johansson. 2014. "Implementation of a scenario-based MPC for HVAC systems: An experimental case study." *IFAC Proc. Volumes* 47 (3): 599–605. https://doi.org/10.3182/20140824-6-ZA-1003.02629.

Rocha, P., and R. C. Rodrigues. 2017. "Bibliometric review of improvements in building maintenance." *J. Qual. Maint. Eng.* 23 (4): 437–456. https://doi.org/10.1108/JQME-07-2016-0030.

Saieg, P., E. D. Sotelino, D. Nascimento, and R. G. G. Caiado. 2018. "Interactions of building information modeling, lean and sustainability on the architectural, engineering and construction industry: A systematic review." *J. Cleaner Prod.* 174: 788–806. https://doi.org/10.1016/j.jclepro.2017.11.030.

Salem, T., and M. Dragomir. 2022. "Options for and challenges of employing digital twins in construction management." *Appl. Sci.* 12 (6): 2928. https://doi.org/10.3390/app12062928.

Shah, K. 2023. "Using digital twin technology to overcome challenges in civil engineering and construction: A review." *Int. J. Eng. Adv. Technol.* 13 (1): 49–57. https://doi.org/10.35940/ijeat.A4305.1013123.

Shahzad, M., M. T. Shafiq, D. Douglas, and M. Kassem. 2022. "Digital twins in built environments: An investigation of the characteristics, applications, and challenges." *Buildings* 12 (2): 120. https://doi.org/10.3390/buildings12020120.

Silva, G., and A. Araujo. 2022. "Framework for the development of a digital twin for solar water heating systems." In *Proc., 2022 Int. Conf. on Control, Automation and Diagnosis*, 1–5. Lisbon, Portugal: ICCAD.

Tanasiev, V., Ș Pluteanu, H. Necula, and R. Pătrașcu. 2022. "Enhancing monitoring and control of an HVAC system through IoT." *Energies* 15 (3): 924. https://doi.org/10.3390/en15030924.

Villa, V., B. Naticchia, G. Bruno, K. Aliev, P. Piantanida, and D. Antonelli. 2021. "IoT open-source architecture for the maintenance of building facilities." *Appl. Sci.* 11 (12): 5374. https://doi.org/10.3390/app11125374.

Wang, Y., J. Kuckelkorn, F.-Y. Zhao, D. Liu, A. Kirschbaum, and J.-L. Zhang. 2015. "Evaluation on classroom thermal comfort and energy performance of passive school building by optimizing HVAC control systems." *Build. Environ.* 89: 86–106. https://doi.org/10.1016/j.buildenv.2015.02.023.

Watson, A. 2011. "Digital buildings—Challenges and opportunities." *Adv. Eng. Inf.* 25 (4): 573–581. https://doi.org/10.1016/j.aei.2011.07.003.

Yaïci, W., K. Krishnamurthy, E. Entchev, and M. Longo. 2021. "Recent advances in internet of things (IoT) infrastructures for building energy systems: A review." *Sensors* 21 (6): 2152. https://doi.org/10.3390/s21062152.

Yang, B., Z. Lv, and F. Wang. 2022. "Digital twins for intelligent green buildings." *Buildings* 12 (6): 856. https://doi.org/10.3390/buildings12060856.