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IoT and Digital Twin: a new perspective for Cultural Heritage predictive maintenance

L. Cecere[a], F. Colace[a,*], A. Lorusso[a], B. Messina[b], A. Tucker[c], D.Santaniello[d]

[a]*DIIn, University of Salerno, Via Giovanni Paolo II, 132 - 84084 Fisciano (SA), Italy*
[b]*DICiv, University of Salerno, Via Giovanni Paolo II, 132 - 84084 Fisciano (SA), Italy*
[c] *College of Engineering, Design and Physical Sciences Brunel University London, UK*
[d] *DiSPAC, University of Salerno, Via Giovanni Paolo II, 132 - 84084 Fisciano (SA), Italy*

Abstract

In the construction sector, the maintenance and monitoring of buildings are of fundamental importance, both in civil and cultural heritage buildings, ensuring their preservation, safety, and proper functioning over time. The preservation of the built heritage is one of the main objectives that a nation must pursue, and thanks to the ever-increasing spread of new technologies, it is possible to apply innovative approaches capable of monitoring in real-time the progressive damage of structures or intercepting sudden situations capable of causing extensive damage. Traditional monitoring methodologies, employed so far, are based on direct inspections and manual data collection, and are often expensive and only sometimes effective. In this scenario, a significant contribution has been made by the Internet of Things (IoT) paradigm, which has made it possible to collect real-time data from sensors placed on the structures to be monitored, thus enabling the implementation of predictive maintenance methodologies. A further contribution to the development of these methodologies has come from the emergence of the concept of the Digital Twin (DT), a digital model of an intended or actual real-world product, system or physical process that serves as an effectively indistinguishable digital counterpart of it for practical purposes such as simulation, integration, testing, monitoring and maintenance. In order to make the DT even more effective, it is possible to link it to the real structure through BIM, i.e. a process applied to existing buildings or monuments that aims not only at the mere restitution of the three-dimensional model but above all at the creation of so-called ‘intelligent models’. The latter is rich in geometric information, including the state of conservation of materials, in which all components are parametric objects with well-defined semantics and can contain all the historical information derived from an adequate documentary analysis. Starting from the above, this paper aims to present a methodology for monitoring an existing building, exploiting innovative technologies based on DT and IoT concepts. The case study analyzed is the Scientific Library of the University of Salerno, and the first results of the experiment are more than satisfactory.

* Corresponding author. Tel.: +39-089-96-4256.
E-mail address: fcolace@unisa.it

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1. Introduction

The historical-cultural heritage of a country is a priceless wealth, a link between the past and the present that encompasses the origins of its nature, the riches of its traditions and the core of its community memory(Jiang et al., 2021). For Italy, this heritage takes on particular relevance, as it is the repository of one of the densest cultural fabrics in the world, a truly great container of works of art, archaeological sites and monuments that narrate millennia of the history of successive civilisations(Colace et al., 2023). The protection of this heritage is therefore indispensable, not only to preserve its cultural legacy for future generations, but also to support the dynamism of the cultural ecosystem that develops around it The growing vulnerability to risk factors, both natural and man-made, as well as the intrinsic complexity of the maintenance and management of these assets, however, call for a revolutionary approach that combines tradition and technological innovation. The ongoing digital revolution makes the Internet of Things (IoT) a valuable tool for the protection of cultural heritage(Lorusso & Celenta, 2023). Through the implementation of sensors capable of transmitting data in real time, it is therefore possible to constantly monitor the condition of monuments, diagnosing any signs of deterioration at an early stage and intervening with targeted actions before the damage becomes irreversible(Casillo et al., 2022a). This proactive vision opens up new horizons in predictive conservation and envisages a substantial transformation of conservation methods(Ribera et al., 2020). In parallel, the Digital Twin concept (DT) is becoming the next challenge in cultural heritage management, as it offers a faithful and dynamically correct digital representation of physical structures(Maksimovic & Cosovic, 2019). Through the integration of DT models with IoT data, a seamless fusion of virtual and real is achieved, enabling not only advanced monitoring, but also the simulation of future situations and the optimisation of intervention strategies(Lorusso et al., 2023). This technological confluence is further enhanced by the adoption of HBIM (Historic Building Information Modeling), which allows three-dimensional models to be elevated to the status of real information databases, so that the state of conservation of the cultural heritage can be documented in detail(Casillo et al., 2022b). This research work aims to investigate the potential offered by the integration of IoT, DT and HBIM in the field of cultural heritage conservation. Through an innovative methodological approach, which uses the most advanced modelling techniques for the creation of high-fidelity digital models, the research also aims to outline a new paradigm in predictive maintenance. The paper is divided into the following sections: in section 2, reference is made to related works; in section 3, the proposed methodology is outlined; in section 4, the methodology is applied to the case study; and in section 5, appropriate considerations and conclusions are made with respect to the proposed methodology.

The practical application of this methodology at the scientific library of the University of Salerno not only confirmed the effectiveness of this approach, but also highlighted the transformative potential of this methodology, laying the foundations for renewed experience in the field of cultural heritage protection.

2. Related works

The development and advancement of new technologies has enabled a gradual application of the IoT paradigm in various fields of work and life. In particular, the integration between data provided in real time by IoT sensor networks and BIM is growing steadily and can be exploited in countless fields of application such as building management during construction, structural monitoring, energy and comfort control in buildings, as well as heritage management and conservation.

In the field of building and construction, more and more cutting-edge applications are introducing IoT technology, which, through the use of special sensors, represents a powerful tool for managing the various phases of a building's life cycle. In recent years, sustainable development has become an increasing priority in planning, becoming the cornerstone of the so-called Smart City concept, which aims to implement the sustainability of buildings through intelligent management systems throughout their life cycle (Chen et al., 2023). This scenario includes the concepts of

Smart Buildings and Smart Home (Sepasgozar et al., 2020), which are becoming increasingly common products of the incorporation of IoT within systems built to address energy-saving problems through automated management of the environment, which can help improve the quality of life and reduce consumption. In this area, research is continuously advancing with the aim of obtaining fully intelligent building envelopes, capable of self-managing and minimising consumption through management mechanisms based on predictive optimisation (Imran et al., 2022), made possible by the introduction of IoT technologies and, above all, integration with BIM. Improving energy efficiency is, therefore, one of the key aspects of making urban environments such as smart cities and connected buildings more sustainable and intelligent. In this context, advanced communication systems, such as IoT systems, play a key role in improving energy efficiency by monitoring and controlling such ecosystems. In this regard, the article (Verde Romero et al., 2024) presents an open IoT edge computing system for monitoring energy consumption in buildings. It is an innovative platform, underpinned by the emerging paradigms of edge and fog computing, which is designed to be compatible with various IoT technologies and prioritises the security of sensitive electrical data by providing detailed measurements of power, voltage and current. The paper (Bereketeab et al., 2024), on the other hand, proposes a method based on reinforcement learning (RL) to optimise the energy consumption of buildings using a simulation software called EnergyPlus. Information considered in the model includes indoor, outdoor and set temperature, heating coil supply, general heating, ventilation, air conditioning (HVAC) supply and occupancy count. Occupancy information such as people counting, location and activity detection are also crucial for smart building management; indeed, in the article (Shokrollahi et al., 2024), the authors focus on the use of passive infrared (PIR) sensors to collect this information. This type of sensor is considered convenient for both privacy and effectiveness. Advances in PIR technology in the efficient understanding and monitoring of occupancy information are crucial for improving energy efficiency, safety and user comfort in buildings. The fusion of BIM and IoT data is a fundamental part of DT processing, through which it is possible to establish interactions between collected data and the built environment, exploit the value of data in the virtual world and improve and enhance decision-making in reality. A clarification of the DT concept is developed in (Khajavi et al., 2019) where, in particular, the advantages of its use in building lifecycle management are highlighted. Wireless sensor network (WSN) integration and data analysis are two necessary components for the creation of a DT, the visualisation of which can be based on a 3D CAD model extracted from the BIM or a customised 3D model of the building(Matos et al., 2022). The DT of a building can use various sensor networks to create a dynamic view of the layout, which allows real-time analysis of the building(Barba et al., 2019). The data collected by the sensors provide an effective model for managing maintenance needs, possible renovations and energy efficiency improvements, with the ability to visualise the hygrometric conditions of the environment in real time. As clarified in (Cecere et al., 2024), the use of sensors in ordinary buildings has become widespread in various applications due to their flexibility and benefits, such as monitoring energy efficiency and thermal performance, hygrothermal properties of walls, air quality, and heating controls. This is the context of cultural heritage buildings with their critical issues with respect to the conservation of artefacts and the environments in which they are located, such as in the case of museums. In general, the preventive conservation of cultural heritage through the application of the DT is generating more and more interest, establishing itself as an extremely topical research topic. One example is the application of HBIM to existing historical buildings, which extends the potential of the BIM method by creating models considered not only as digital representations of their geometry, but as dynamic models, enriched by different levels of real-time information derived from sensors and IoT technologies, allowing for better management and preservation (Saricaoglu & Saygi, 2022). Future development is aimed at the elaboration of increasingly accurate machine learning techniques, in order to obtain a Heritage Digital Twin (HDT) that can guarantee an increasingly complete and innovative cultural heritage assessment and control experience.

3. Methodology

The methodology under study sets the objective of continuous monitoring of a building for the purpose of predictive maintenance to support expert users. This methodology is based on two main cornerstones, IoT and DT. This objective is based on a series of preparatory and consequential processes (Fig. 1).

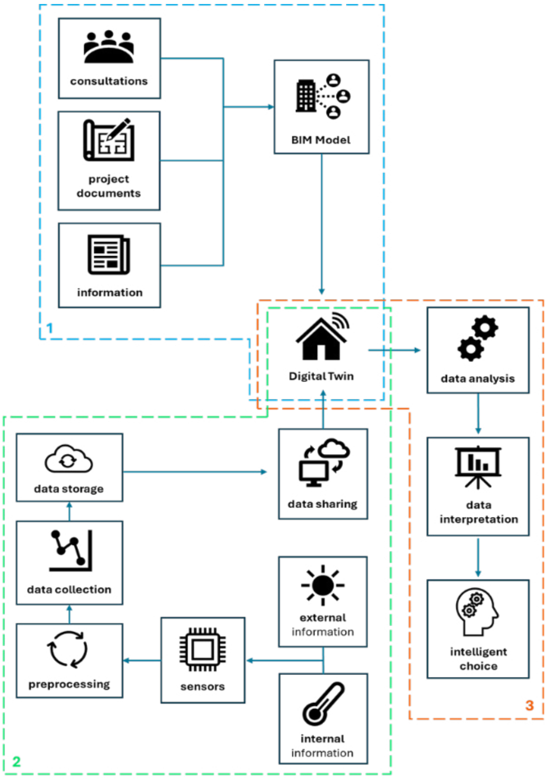

Fig. 1. Proposed methodology

Based on the initial project drawings, the Building Modelling Information System (BIM) version was developed. At this stage, special attention was paid to the measurement and definition of the building elements. During the development, direct field inspections were carried out to identify areas with problems that were not clearly outlined in the design documents and technical reports. These inspections fostered an understanding of the interconnection and interaction between the various components, as well as their connection to their surroundings, and improved the understanding of their functions. Interaction with experts in the field was necessary for optimal project management. The material and technical characteristics were described in detail in the BIM, using different families and variants for each category, as the external and aesthetic characteristics vary depending on the environmental location. It should be noted that the model reaches a level of detail 300 (LOD 300), which corresponds to a degree of graphical accuracy that includes dimensions, material, orientation, shape and integration of components. As far as BIM modelling is concerned, the information describing the model is static information, derived from the initial design information, and in this way it was possible to specify the various layers of the elements and the type of material of which each architectural element is made. Following the BIM modelling, the data acquisition phase is prepared through sensor systems and IoT technologies for monitoring the physical environment. In accordance with the previous sections, data are collected from the internal and external environment in real time over a predefined period through devices equipped with specific sensors. The collected data are shared with other networked devices, thus creating an intelligent ecosystem. The devices, based on various communication protocols, facilitate the transmission of data to the processors. In particular, the MQTT protocol introduces a communication broker between client and server, increasing the security of information. Sensed signals are forwarded to a gateway, which acts as a bridge for the transfer of data to the cloud, ensuring adequate security management. Furthermore, through an IoT platform, data is displayed on devices or dashboards that update in real time, simplifying the interpretation and storage of data and making it possible to remotely monitor the infrastructure at any time. Ultimately, the DT is created through the combination of the BIM model and data from the IoT platform. In fact, the static data of the BIM model is supplemented by dynamic data recorded by the various sensors installed. This is a reliable virtual model that updates in real time and emulates the operation of the building as reliably as possible. The output provides an accurate simulated representation of the physical design. In concrete terms, the DT allows predictive maintenance strategies to be developed and different scenarios to be simulated. Modifying the input data makes it possible to predict structural or environmental reactions of the system. The data analysis part provides the basis for optimal decisions regarding the operation and maintenance of the building.

4. Case study

The proposed work developed from a real case study: the Scientific Library of the University of Salerno. This is a building designed by Prof. Arch. Nicola Pagliara that is located on the Fisciano campus, on over 2,000 square metres and spreads over eight levels of which the ground floor, three basement levels and four raised levels. It has a total capacity of approximately 350000 bibliographic units and brings together the library collections formerly belonging to the Faculties of Mathematical, Physical and Natural Sciences, Engineering and Pharmacy. The building is reminiscent of an industrial design, as if representing the knowledge industry. The choice of material elements characterises its façade because the use of stone and marble elements with grey bricks gives a sense of movement to the structure. The choice of this study is justified by the fact that this is a relatively young structure that shows the first hints of decay, so it is functional to analyse the evolution of a given decay over time, from the first signs to the most substantial damage.

For the monitoring of the building, various sensors were used to detect different parameters. The choice is crucial since it is possible to analyse both purely architectural and structural or energy aspects. The sensor system that is used is complex, but allows information to be recorded concerning both the environmental conditions of the surrounding area and the micro-environmental conditions of the building itself.

For the monitoring of weather and climate conditions, a WS3500 model weather station was installed, which integrates several sensors and is equipped with a colour LCD display that provides a clear, real-time view of the data collected. The integrated all-in-one wireless sensor array collects data on temperature, humidity, atmospheric pressure, wind speed and direction, UV radiation, solar radiation and precipitation. Specifically, the station is equipped with the following sensors:

- BME680, is a multifunctional digital sensor capable of monitoring various environmental parameters, including temperature, humidity, barometric pressure and volatile organic compounds (VOCs). This sensor operates over a temperature range of -40°C to 85°C, with maximum accuracy when the temperature varies between 0°C and 60°C. Under these conditions, it can detect relative humidity with an accuracy of ±3%, pressure with an accuracy of ±1.0 hPa and temperature with an accuracy of ±0.5°C. To measure air quality, the 'BME680' uses a MOX (Metal-Oxide) sensor that detects VOCs in the air by changing resistance when the metal oxide is heated.
- SI1145, is a digital sensor with a light detection algorithm calibrated to calculate the UV index. This sensor approximates the index based on visible and infrared light from the sun. Despite this approximation, studies have shown that the data generated by the sensor is extremely accurate. The sensor operates in a temperature range of -40°C to 85°C. The IR sensor has a wavelength in the spectrum between 550 nm and 1000 nm (centred on 800 nm), while that of visible light is between 400 nm and 800 nm (centred on 530 nm).
- PMSA003, is designed to monitor air quality, focusing on the detection of contaminants such as particles, pollutants and gases harmful to human health. This device uses laser scattering technology to illuminate airborne particles. A microprocessor calculates the equivalent particle diameter and determines the number of particles with different diameters present in a given volume of air. The data is updated every second, providing information on the concentration of PM1.0, PM2.5 and PM10.0 particles in both standard and ambient units.

The station is also equipped with a 'rain gauge', which is a device used to measure the amount of rain that falls in a given period of time. It consists of a collecting cylinder or funnel that collects rainwater and a measuring mechanism that records the amount of water collected. This instrument is essential in a meteorological station and is the reason why the station must be located in an open, unobstructed place to accurately record rainfall levels.

For wind analysis, there are two sensors, the first is the 'Wind Speed sensor' specifically designed to detect and measure the speed of moving air. Using an ultrasonic anemometer, this sensor is able to detect wind speed in real time. The ultrasonic anemometer technology uses high-frequency sound waves to calculate the time of flight and thus determine the wind speed. The data collected by this sensor can be viewed directly on the weather station display and can also be recorded for detailed analysis later. This information is crucial for various applications, including climate studies, environmental monitoring and weather forecasting. The other wind sensor is the 'Wind Director sensor', which is a device that makes use of an internal magnetic sensor to detect changes in the direction of the earth's magnetic field caused by wind. Changes in structural conditions and materials are monitored using cameras, video cameras and thermal imaging cameras. These devices capture images that can be analysed to detect deformations, cracks and other signs of damage. Through the images of these instruments, changes in materials can be detected and consequently phenomena such as corrosion, or the effects of moisture condensation can be studied. Using computer vision techniques with the Python programming language, the images captured by the cameras can be automatically processed to extract useful and manipulable information.

4.1. BIM modelling

In this phase, the BIM model was developed using the Revit software provided by Autodesk. Starting with the plans of the various levels, the building was modelled: starting with the lowest floor and the external perimeter walls, the architectural elements were modelled and then the so-called design parameters were defined. The forms were modelled by focusing first of all on the stratigraphic differences of the masonry that makes up the building: identifying different materials and construction techniques to characterise the different families of components with which to create the 3D model, allows a model to be obtained that is as similar as possible, in appearance and behaviour, to the real one. After all these steps, therefore, the digital model of the library was created, which contains all the geometric characteristics and physical properties of the materials that compose it.

The fundamental step, at this stage, was the definition of new design parameters, necessary for the subsequent visualisation in BIM of the data coming from the sensors, through Dynamo. Design parameters are those which can be added to certain categories of elements in a project and which, in our case, were applied as instance parameters, i.e. they allow the properties of the element they refer to to be changed.

4.2. Data Acquisition on ThingsBoard

The second part of the work was based first on the acquisition of data from the sensors and then on the collection and storage of this data on the ThingsBoard platform. The data from the sensors arrive at the gateway, which in this case is a concentrator, the Raspberry Pi, which cyclically interrogates the sensors and stores the data recorded by them in order to send it to the cloud. Subsequently, the data on the cloud is collected by ThingsBoard. This is an IoT-based cloud platform designed for device management, which is able to read and display data correctly in real time. The platform allows, not only to visualise, but also to monitor and control data in a secure way; it also collects and stores information from the last telemetry performed and, thanks to the presence of integrated widgets, allows both an intuitive visualisation of incoming information and the possibility of customising the interface. To start storing data, an authentication token was generated to allow access to the platform; it was used to establish a secure connection between the devices and the platform, allowing them to send data and receive instructions without compromising the security of the transmitted information. In short, the token acts as a secure and authorised access key to interact with the IoT platform. Each sensor has its own ID and access token that allows it to send data and be recognised by the platform. This made it possible to filter the type of parameter to be displayed according to the selected sensor. The heart of the system is the Raspberry Pi, which acts as a concentrator and is nothing more than a complete low-cost minicomputer that acts as the physical hub of the system. This device acts as a link between all the sensors: it recognises data from the sensors thanks to an identification token, collects it and interacts with the cloud system by sending it to the platform. Thanks to this configuration, it was possible to store the data on ThingsBoard and visualise it through the corresponding dashboards (Fig. 2), i.e. graphs showing the trend of the values.

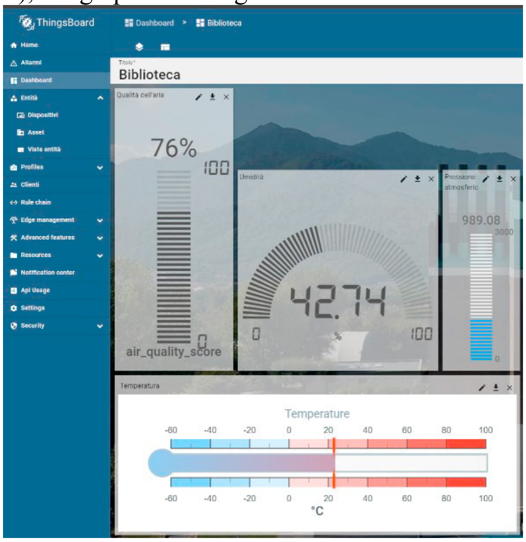

Fig. 2. Dashboard by ThingsBoard

4.3. Integration of data into the BIM model

The next step involved the integration of data from ThingsBoard into the BIM environment using Dynamo. The accurate integration of data between ThingsBoard and the BIM model ensures consistency in the flow of information by defining correlations between the data and the corresponding elements in the model. Keeping the DT up-to-date is essential to reflect the current condition of the actual building, so Dynamo is used to implement a continuous monitoring system that is able to update the data in the BIM model in real time. Dynamo is a visual programming tool that works with Revit and is able to extend the software's capabilities by providing access to APIs (Application Programming Interfaces) in an easier and more straightforward manner. Instead of typing a code, in fact, Dynamo is used by manipulating graphical elements called nodes and, through their connection, generates a script that will allow us to read sensor data in Revit. Dynamo offers libraries of predefined nodes that make it easy to connect, combine and modify model inputs and outputs, but it also allows the creation of custom nodes, which are essential for automating tasks and simplifying workflow. The connection between ThingsBoard and Dynamo was made possible through a series of nodes with defined inputs and outputs, facilitating a smooth and reliable data exchange between the two systems and ultimately allowing the data to be read directly into the BIM model. Once the external data was merged with the digital model data, we finally arrive at the actual DT understood as a representative model of the work and linked to it so as to replicate its behaviors and structural stresses in real time and the environmental conditions to which it is subjected.

5. Conclusion and future development

The objective of the present work was to provide a system for monitoring the environmental conditions of the Scientific Library of the University of Salerno, on the Fisciano campus. For this purpose, the DT of the building was implemented, connecting the three-dimensional virtual model, to the incoming data stream from IoT sensors. This monitoring approach, in contrast to classical methods, allows access to data in real-time and gives the possibility of timely intervention in the building in case of need. Specifically, the methodology applied was based on the one hand on modeling in a BIM environment, using Revit software, on the other hand on collecting and storing, on a particular IoT platform, incoming data from the sensors and, then, on integrating the data with the digital model, via Dynamo. This integration generated the actual DT that allows real-time visualization of various parameters and facilitates analysis to simulate future scenarios. Overall, the results obtained were satisfactory, and the incoming data from the sensors can be visualized, in real-time, directly in the BIM environment. The results, of course, can be further improved: by implementing sensing, it will be possible to develop a more complex network of data, which would enable more accurate estimation and, consequently, the ability for building managers to make targeted and intelligent decisions; by applying machine learning techniques, it will be possible to define the scheduling of interventions, automatically improve the quality of data, and train machines to make predictions and draw conclusions without requiring specific instructions.

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