Low-cost Real-Time monitoring with BIM Integration in a Polluted Urban Environment

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Abstract

This research focuses on developing a low-cost, real-time monitoring system integrated with a Building Information Modeling (BIM) ecosystem to improve indoor air quality and comfort in polluted urban environments. The system uses a 3D parametric BIM model, sensor arrays, and microprocessors, communicating via the Arduino Cloud. It collects environmental data, including temperature, humidity, pressure, illumination, and carbon dioxide levels. When CO2 concentrations exceed comfort thresholds, the system assesses external pollution levels using data from the IQAir database before opening windows. A servomotor device controls window openings, adapting the duration based on pollution and CO2 data to minimise indoor pollutants.
The procedure involves two key processes: detailed 3D scanning using the Leica BLK2GO laser scanner and real-time environmental monitoring via the Arduino platform. The integration of BIM, Python code, and Dynamo enables the system to adapt the building's ventilation in response to fluctuating conditions. Data collected from this system is compared with factory-calibrated sensors like AirThings Wave Plus, showing similar results over a 7-day period. This project is part of the MUSA-Multilayered Urban Sustainability Action and aims to further explore natural methods for CO2 absorption within indoor environments.

1. Introduction

In urban environments, maintaining indoor air quality and occupant comfort is increasingly challenging because of high levels of external pollution and limited ventilation opportunities. Effective indoor air quality management is essential not only for health but also for comfort, productivity, and overall well-being, especially in dense urban settings where pollution frequently exceeds healthy levels. The rising interest in sustainable buildings and smart technology integration calls for innovative methods to monitor and control indoor environments efficiently. This study presents a novel, low-cost, real-time monitoring system that combines Building Information Modeling (BIM) and Internet of Things (IoT) devices to create a responsive indoor environment. Through a Digital Twin approach, which bridges physical and digital realms, the system enables bi-directional communication between the building's physical environment and a digital 3D model. This configuration allows for dynamic adjustments to air quality in response to real-time sensor data, facilitating remote supervision and optimisation of indoor conditions. The aim of this research is to develop a scalable, economical solution for monitoring and managing indoor air quality in polluted urban areas. By leveraging IoT devices, cloud-based communication, and BIM, this approach offers a flexible and automated solution capable of integrating with existing building management systems. In doing so, the study addresses key challenges in affordable smart building solutions, advancing real-time environmental monitoring and adaptive response mechanisms within a BIM framework.

2. State of the art

The subject of this research is the development of a digital 3D monitoring system for indoor environments, utilising low-cost devices. The main aim is to improve indoor comfort and air quality through real-time monitoring and intervention strategies.
A significant aspect of the research is the creation of a Digital Twin, integrating Building Information Modeling (BIM) with Internet of Things (IoT) devices and sensors. This system allows for bi-directional communication between the physical environment and its digital representation, enabling self-awareness, optimisation, and remote supervision (Bolognesi and Signorini, 2021). The digital twin can be used for self-awareness, self-optimisation, and remote supervision.
One of the primary reasons for the existence of digital twin is the ability to connect the model itself with physical reality (Del Giudice and Osello, 2021) ; it is physically impossible to achieve this result by directly connecting sensors to the digital model. It involves the use of digital technologies and data to develop a comprehensive, dynamic model that replicates its real-world counterpart throughout the entire lifecycle, from design and construction to operation, maintenance, and ultimately, decommissioning and demolition (Honghong et al., 2023).
Despite BIM's potential for lifecycle management, it falls short of considering human interactions and real-time asset behaviour (Matarneh et al., 2019). Sensors and IoT devices aim to enhance high-fidelity BIM models by providing real-time data streaming, improving construction and operational effectiveness. However, BIM and IoT integration is still in progress (Tang et al., 2019). The Digital Twin concept aims to overcome BIM limitations. It integrates diverse types of information, including architectural and engineering designs, structural data, sensor inputs, and building system details. It is developed using a combination of Building Information Modeling (BIM), Internet of Things (IoT) devices, cloud computing, and data analytics. The main aim of creating a DT in construction is to enhance project understanding, simulate various scenarios, optimise performance, and support better decision-making throughout the construction process. (Revolti et al., 2024).
Although lacking a universal definition for construction or infrastructure assets, the Digital Twin is outlined by key features: Bi-directional Synchronisation, Integration of Physical and Virtual Entities and Lifecycle Management (Jones et al., 2020). Digital twins involve continuous, bi-directional data flows

between the physical and virtual entities, allowing for real-time synchronisation. This ensures that changes in the physical asset are reflected in the virtual model and vice versa, which helps in monitoring and controlling operations effectively. The digital twin concept integrates a physical entity with a virtual counterpart, enabling simulation, analysis, and optimisation. This integration uses sensor data to create a high-fidelity virtual representation of the asset, enabling comprehensive operational insights.

Figure 1. Case study is a building belonging to Politecnico di Milano, Leonardo Campus, in Milan

Digital twins support the entire lifecycle of the physical asset—from design and construction to operation and decommissioning. They help track the current state, predict future conditions, and assist in decision-making processes across different lifecycle phases, ultimately leading to improved efficiency and reduced costs. Supporting technologies for Digital Twins include wireless sensor networks for data collection and data analytics, encompassing artificial intelligence (AI) and machine learning (Khajavi et al., 2019). The virtual copy, visualised in a 3D model, offers a real-time view of the built asset, enabling dynamic analysis, building efficiency, comfort enhancement, and informed decision-making. The systems were primarily designed to connect sensors directly to the PC, but remote access could pose a challenge. (Tsani and Subardono, 2019) introduced a solution to this issue by using the Arduino Cloud as an exchange hub for data.

The digital ecosystem (Lynn et al., 2020; Malhotra et al., 2021; Syed et al., 2021) demonstrated the possibility of achieving optimal results in connecting sensors and digital twins using IoT tools. This strategy allows sensors to be connected to the digital model via the internet, with no direct connection (Natephra and Motamedi, 2019). A comprehensive literature review of this methodological approach has been undertaken (Valinejadshoubi et al., 2021), highlighting the difficulties encountered by individual case studies. In the light of the state-of-the art, data transmission via Arduino Cloud was eventually chosen to connect the BIM model with the sensors to establish a real-time digital twin system.

The case study (figure 1) is a building in Milan, belonging to the Leonardo campus of the Politecnico di Milano. The building is a two-storey office, where various experiments occur under the aegis of the MUSA project, which will be considered for integration with this research project. The starting point of this procedure is a detailed survey using a handheld Leica BLK2GO laser scanner. This scanner can capture up to 420,000 data points per second and integrate LiDAR SLAM, visual SLAM, and IMU (Inertial Measurement Unit) technologies.

3. Methodology

The strategy behind this research project was completely theorised, working out every single step that creates the connection between the actual building and its digital twin. It was necessary to think up a system of hardware and software devices that could realise this connection. The ecosystem is composed of a 3d parametric BIM model, an array of sensors and microprocessors, and a servo system.

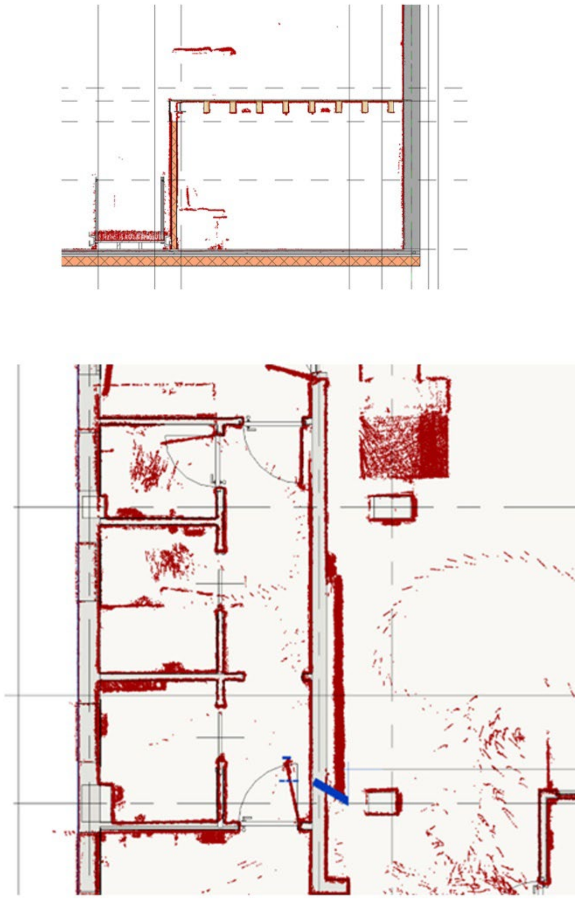

Figure 2. Model in BIM environment from a point cloud made with Leica BLK2GO mobile laser scanning station

This scanner can capture up to 420,000 data points per second and integrate LiDAR SLAM, visual SLAM, and IMU (Inertial Measurement Unit) technologies. These features allow the scanner to move through three-dimensional space while capturing accurate, high-resolution data of the interior environment. The scanning process was completed in two sessions, each lasting approximately 20 minutes. The resulting point clouds, containing around 109.36 million points, were combined using proprietary Cyclone Register 360 software. The point clouds were aligned, merged, and exported in CPR format for subsequent modelling in a BIM environment. The final three-dimensional model of the case study building was created using BIM tools, ensuring the digital representation accurately reflects the physical structure. The interior space scanning process required two surveys, totalling 20 minutes, which resulted in the generation of two separate point clouds. The two-point clouds were combined into a single array of approximately 109.36 million points using Cyclone Register 360 software. The clouds were aligned and exported in CPR format for further modelling in BIM format. Three-dimensional modelling was then performed with a BIM tool (figure 2). The building was modelled in its main geometric components, masonry, structural, and closures. The modelling was designed to limit the maximum distance between a model point and its corresponding cloud point to 2.5 cm. This precision can be framed into Level of Geometry (LoG) 300 – Detailed Geometry, part of the Level of Information Need (LOIN) framework (ISO 19650-1). It represents an accurate geometry with precise dimensions, usually representing what is required for construction documentation and detailed design. This precision level is enough to depict the element's design with precise dimensions, positions, and orientations, allowing it to be used for design coordination and documentation.

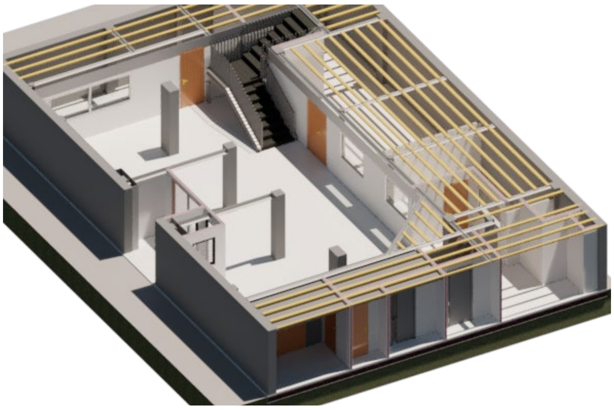

Figure 3. Customised BIM families were developed to represent accurate geometry as required for construction documentation.

Customised element families were made when the standard components did not meet the required geometric precision standards (figure 3).
Once the building and its context were defined, a strategy was needed to exchange information between the real and digital model (figure 4). Numerous examples in the literature emphasized the necessity to write a programming code that can connect the two models. The challenge was to design a workflow that was both unique and flexible, allowing it to be applied to various building types while enabling real-time data flow. The most demanding part of this work was the creation of the code to update the digital twin with data from the Arduino sensors. The initial problem was writing the software to allow the Arduino board to read the environmental data detected by the temperature, humidity, and CO2 sensor and transmit it to the digital twin ecosystem.
Subsequently, because of the stringent computer security protocols in the case study area, the system was initially tested with the connection to an external Wi-Fi network.
This initial procedure allowed the system to read the values and transmit them to an external dashboard provided by the Arduino platform. To solve the security problems, the entire IT structure of this work was connected to a proprietary Cloud system, called Arduino Cloud. All access to the sensors, therefore, occurs through this cloud and not directly. Through the cloud, it was possible to both acquire data and/or completely update the code. The decision to use this cloud ecosystem was influenced not only by its compatibility with the real-time monitoring system but also by its alignment with the low-cost objectives of the overall methodology presented in this paper.
The code is customised, but it relies on various libraries that play specific roles in establishing and maintaining the connection with Arduino Cloud. Some libraries allow the script to interact with Revit, while others are designed to manage functionality. Other libraries provide tools to control the IoT platform, for sending and receiving data from remote sensors.
After the environment has been established, the algorithm provides a secure method of logging in, known as OAuth2 authentication. This process is popular in applications that work with API, to ensure that only authorised processes can access sensitive data or services. Instead of using a traditional combination of user and password, the method creates an authentication "token" that serves as a key to unlock access to the IoT platform. The token is created with a unique string of characters called the "client ID." Using this system, the code configures an OAuth2 client, allowing this customised ecosystem to log in to the Arduino Cloud securely. Once authenticated, the procedure establishes a session connection with which data can flow continuously.
This condition allows the system to exchange data with no need to re-authenticate each time, as long as the token remains valid. This Dynamo/Python code can interact with the IoT platform in real time, which is a paramount feature for making digital twin work. Data acquired from the Arduino cloud are endless strings of text, which must be organised in libraries and manipulated to be readable. The Python programming language has tools to interact with these libraries and extract the required values of temperature, humidity and carbon dioxide. These data are indispensable for the ecosystem to function. Depending on the real-time supply of this data, the procedures for operating the digital twin are then activated.
The sensor array comprises a set of temperature, relative humidity, pressure, illumination and a second sensor dedicated to CO2 measurements. To communicate with the 3D model, this array is combined with an Arduino microchip-based platform that transmits the Wi-Fi signal. Communication between the model and the sensors is not done directly, but through a cloud system called Arduino Cloud. The system collects the data mentioned above to monitor thermal comfort. Together with this data, carbon dioxide in the air is detected. Once the maximum comfort threshold for the room has been exceeded, common usage suggests opening the windows to promote air exchange. Different regulations exist to define the CO2 limit threshold. For this study, Directive 2009/152/EC will be used, which sets a time-weighted average concentration limit of 2000 parts per million. European legislation lacks guidelines for room CO2 reduction, yet improving ventilation proves highly effective. Because of a polluted outdoor environment, this procedure cannot be implemented for an extended period, as it would negatively affect CO2 levels and air quality.
The system's third component is a servomotor device. It connects the Arduino microprocessor to the window frame for opening. This system comprises a device that precisely controls the angular movement of an axis through a servomotor, a control circuit, and a potentiometer. Under certain circumstances, opening the window frame would significantly worsen air quality because of PM2.5 and PM pollution. Therefore, at a defined time interval, the digital model acquires pollution data. A maximum pollution threshold is defined, beyond which the air exchange will be limited to 10 minutes. Otherwise, the air exchange will be conducted until the CO2 value falls below the previously defined threshold value.
The engine driving the procedure is an ad hoc code written in Dynamo and integrated with Python working within BIM. This ecosystem dialogues respectively with: the sensors that detect environmental data inside the case study, the pollution data outside and the engine that drives the window opening. The environmental data are provided by a couple of Arduino board that transmit in real time values of Temperature and Humidity. The transmission from sensors to BIM is made through Arduino

Cloud. Every ten-minute cycle, the system detects carbon dioxide values (along with other data useful for environmental comfort). If the value is higher than the limits, it performs an external pollution check. This control occurs through a Web API (Application programming interface), with a query to the IQAir database, which provides data on a global pollution value for the Milan city area. If the value is above a certain threshold, it limits the window opening to the duration of the cycle.

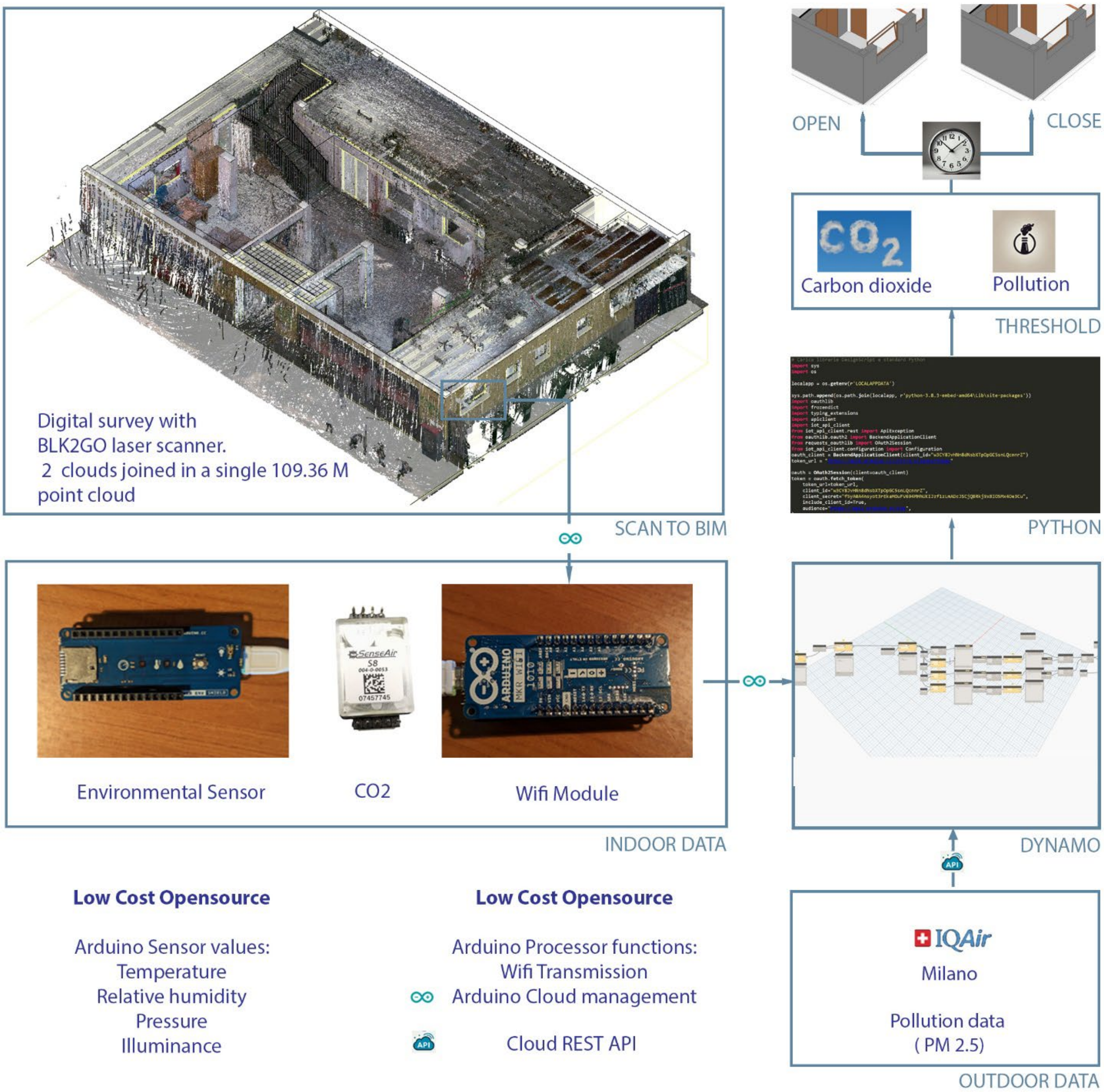

Figure 4. Digital Twin Workflow. The real time responsiveness of the actual building is ensured by Arduino Cloud, which is the connection between the model, the sensors and the actuators.

If the pollution value is below the threshold and the CO_2 is over its maximum allowed values, the procedure continues with the window opening until the next cycle. The window will be closed when the carbon dioxide value falls below the threshold value. The frame's angular movement directly affects the corresponding geometry in the BIM model by altering its digital twin window. The change is quantified in terms of the window area that provides the change. This system overcomes the binary open/closed window alternation, exploiting the potential of the digital twin. It will be possible to acquire an actual quantitative measure in the volume of air when an airspeed detector will be installed. The whole digital twin will optimize the reduction process of CO_2 concentration by improving the quality of the environment.

The sensor array and microprocessors were completed and operational. The system is currently operating under a digital shadow environment, where data flows from actual building to the digital one. The environmental data are acquired as a single pollution value for the whole city of Milan, which considers several factors. The servo system part is currently under development and the research is performing a series of punctual experiments, with the aim of using low-cost technologies.

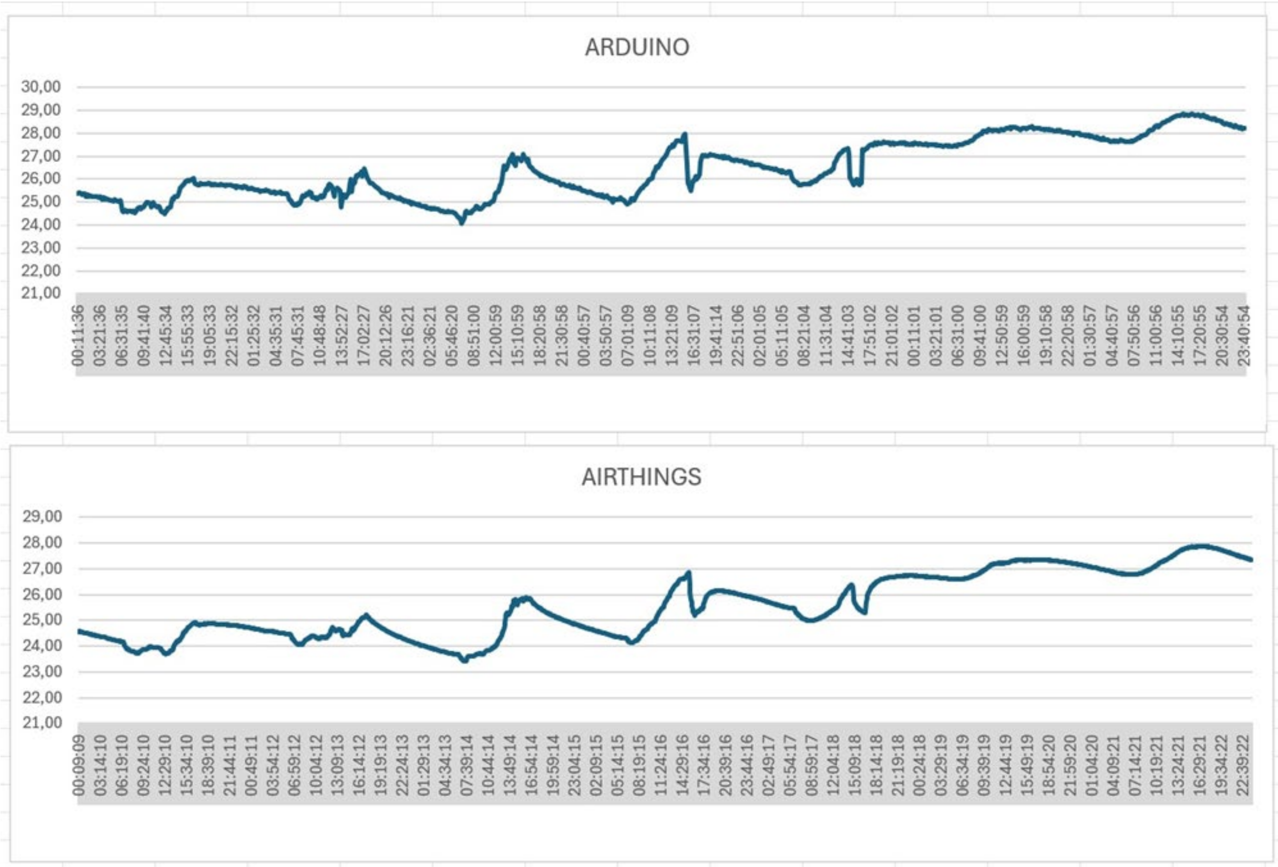

Figure 5. Comparison of one week's temperature data collection between the Arduino ecosystem, the subject of this research work, and the Airthing Station described. The trend is super-imposable and the average deviation between the values is below the threshold of one degree centigrade.

4. Discussion and Future Development

This work details an ongoing procedure implementation. At the time of writing, the system detects and transmits environmental and carbon dioxide data. The data got by the described process was calibrated and compared with that of a factory-calibrated sensor, the AirThings Wave plus environmental sensing station. This station is a proprietary solution much more expensive than the Arduino system and detects Radon, Carbon Dioxide, Temperature, Airborn Chemical, Air pressure and Humidity. A 7-day parallel measurement period was performed, which provided very close data in terms of absolute values between Arduino and AirThing station (figure 5).
The Arduino system is an open-source technology with a low implementation cost, which allows a very wide flexibility in data management and remote transmission. There are two main handlers within the case study area for querying pollution data. The reason IQAir was chosen over ARPA (Regional Agency for Environment Protection) is because it offers real-time data deployment, which is crucial for the procedure to work.
Because of its algorithmic nature, the web API protocol structured within Dynamo can easily apply to other service providers, guaranteeing optimal functionality. The last phase that closes the circle of the digital twin, i.e. the physical management of the fixture, was conceived in conceptual terms, but not tested. To operate the opening and closing of a window frame using servo actuators, addressing mechanical and electrical difficulties is essential. Additionally, it is necessary to proportion the effort induced by the mechanism according to the type of window frame being processed. Second, it is necessary to solve the problems relating to the electrical connections between the Arduino platform and the actuators that will perform the actual movement. This type of mechanism has a series of parameters that regulate its operation, which need converters of various kinds. The first step taken in this direction is the installation of a MOSFET-type device, a current flow regulator in a circuit, used as a switch and as a voltage amplifier.

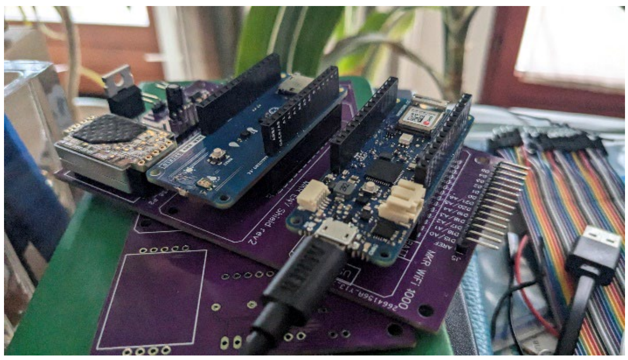

Figure 6. The current development of hardware part of digital twin. The cable shown on the right has been replaced by a customised board that optimises connections by reducing troubleshooting and voltage surges.

A single hardware platform capable of optimising the electrical connections between individual components is currently being tested (Figure 6). The board in the figure was designed and built

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based ad hoc on a model in Eagle Cad, an electronic design automation (EDA) software that allows printed circuit board (PCB) designers to connect schematic diagrams seamlessly.
This model provided the connection between the three main components, the Wi-Fi board, the board containing the temperature, humidity, pressure and illumination sensors and the third component that detects co2. Eventually, the MOSFET-type hardware was installed, but its operation is still under development.
The procedure could find future paths of development through implementation in different areas of real-time monitoring: artificial intelligence for predictive maintenance and Behaviour Modeling and interaction with the Digital Twin.
In the former case, the current system through implementing AI could provide a predictive analysis of air quality and other environmental factors. Stored historical data could anticipate co2 peaks, optimising ventilation in advance.
In the second case, users' behavioural data and habits could improve system adaptation. This could analyse the punctual needs of the users, e.g. opening at a time compatible with the usage hours of the examined premises.
Finally, the system could respond to including plant essences within the rooms. Their optimal placement for co2 storage could be integrated into the monitoring as an aid to the operation and efficiency of the system itself.

5. Conclusions

The ecosystem underlying this work is of great interest because it allows considerable flexibility in terms of both physical and digital connections. The described procedure, once tested and completed, will serve as the basis for a digital system. This system facilitates the real-time response of the model to the building's stresses.

Acknowledgment

Contributions have been described following CRediT (Contributor Roles Taxonomy). CB and DD: concept
CB: Project Administration, Supervision, Validation, Digital Survey. DD: Development, Data Curation,
Methodology, Testing, Visualisation.

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