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Indoor Air and Thermal Quality in School Buildings: Demonstration of BIM-Integrated IoT Window Signaling System

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Abstract. Indoor Environmental Quality (IEQ) plays a crucial role in the health, well-being, and cognitive performance of students in school environments. This study presents the integration of Building Information Modeling (BIM) and Internet of Things (IoT) sensors for real-time IEQ monitoring and dynamic ventilation control. A BIM-integrated window signaling system was developed using visual programming to process real-time sensor data and provide feedback on optimal window operation times. The methodology consisted of five phases: (1) development of a BIM model of the case study and calculation of window opening time, (2) on-site deployment of an IoT sensor system, (3) integration of real-time environmental data into the BIM model, (4) generation of a continuously updated digital twin for IEQ assessment, and (5) comparison between calculated ventilation times and measured environmental parameters. The system was tested in two classrooms of a school in Rome, Italy, where temperature and CO_2 concentration were continuously monitored. The results indicate that the calculated ventilation schedules effectively maintained indoor temperatures within recommended thresholds. However, CO_2 levels frequently exceeded the guide value threshold in one classroom, revealing discrepancies between the expected and actual window opening behaviors of occupants. The study underscores the role of occupant compliance in ventilation effectiveness and demonstrates how BIM can function as a dynamic decision-support tool by integrating real-time environmental data, automated parameter updates, and graphical trend visualization.

Keywords: School Buildings · BIM · IAQ · Thermal Comfort · IoT sensor · IEQ

1 Introduction

Research has consistently demonstrated that the quality of the indoor environment significantly impacts occupants' health, comfort, and productivity, particularly in educational settings where children spend a substantial portion of their day [1, 2]. Schools often face challenges in maintaining optimal indoor environmental quality (IEQ) due to varying

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occupancy patterns, outdated infrastructure, and inconsistent ventilation strategies. Poor air quality, inadequate lighting, and uncomfortable temperatures can negatively impact both students and teachers, leading to reduced engagement and increased absenteeism [3]. Children's perceptions of thermal comfort and indoor air quality are particularly relevant in this context. Studies indicate that children's comfort levels are influenced by their subjective experiences of temperature and air quality, which can significantly affect their concentration and overall academic performance [4]. For instance, research has shown that children in classrooms with better thermal comfort and air quality report higher satisfaction levels, which correlates with improved learning outcomes [5]. Furthermore, children are more sensitive to indoor air pollutants due to their developing respiratory systems, making it imperative to monitor and manage indoor air quality (IAQ) effectively in school environments [6]. The literature suggests that factors such as noise levels can also impact children's thermal comfort, with increased noise leading to decreased comfort levels [7]. This interplay between various environmental factors highlights the need for a holistic approach to IEQ management that considers children's perceptions and experiences. Key factors such as thermal comfort, IAQ, lighting, and acoustics are essential components of IEQ that necessitate continuous monitoring and assessment [5].

With growing recognition of IEQ as a key factor in learning, educational institutions increasingly seek effective monitoring systems that deliver real-time data to support informed decision-making [8]. The integration of Building Information Modeling (BIM) with Internet of Things (IoT) sensors, enhanced through visual scripting, provides an effective framework for monitoring and improving IEQ in existing school buildings. The application of BIM technology allows for the creation of detailed digital representations of school buildings, which can be augmented with real-time data from IoT sensors to provide a comprehensive overview of indoor conditions [9]. This integration not only facilitates the visualization of environmental data but also supports the identification of patterns and trends that can inform maintenance and operational strategies [10]. Moreover, the integration of IoT sensors within BIM frameworks facilitates a proactive approach to IEQ management. Continuous monitoring of environmental parameters allows for the early detection of issues such as poor IAQ or inadequate thermal comfort, which can be addressed promptly to mitigate their impact on occupants [11]. The use of real-time data not only enhances the responsiveness of building management systems but also empowers educators and administrators to engage in informed discussions about resource allocation and facility improvements [12]. To implement these connections with real-time data, visual scripting applications are often used in BIM environments. Visual scripting, as a method of programming that allows users to create scripts through graphical interfaces rather than traditional coding, offers a user-friendly approach to developing complex algorithms for data processing and analysis within BIM environments [13, 14]. By employing visual scripting tools, stakeholders can easily manipulate and visualize data from IoT sensors, enabling them to make data-driven decisions regarding the management of indoor environments [9]. This capability is particularly beneficial in educational settings, where the ability to quickly adapt to changing conditions can enhance the learning experience and promote a healthier environment for students [15].

The effectiveness of dynamic control and monitoring systems relies on both advanced modeling and software components, such as modeling and scripting, as well as sensing, control interfaces, and actuator systems. This includes IoT sensors designed to acquire and transfer data on Indoor Environmental Quality (IEQ) to information models, ensuring real-time monitoring and adaptive control of indoor conditions. In terms of hardware components, previous work has demonstrated the use of window signalling systems to support natural ventilation and indoor environmental quality in office buildings. Ackerly and Brager [16] examined window signaling systems in 16 U.S. buildings, finding that their effectiveness depends on visibility, clear logic, and integration with motivational strategies for comfort and energy efficiency. Their study revealed that occupants engage with signals mainly when discomfort arises, limiting proactive influence. While feedback systems can enhance satisfaction by reinforcing perceived control, challenges remain in designing systems that align with diverse occupant behaviors, such as preferences for fresh air over strict temperature control. Recent work of the authors [17] demonstrated that window signalling systems can support human-window interaction in work environments by integrating a multi-domain control algorithm to inform optimal window opening time depending on indoor and outdoor temperature, air quality and heating status. The study compared existing and new conditions over six weeks, analyzing the impact of real-time feedback on window operation based on air quality, thermal comfort, and energy efficiency. Results showed a 55% reduction in ineffective window use, improved CO_2 levels, temperature stability, and occupant satisfaction. Participants found the system understandable, effective, and preferable to digital notifications, providing design insights for optimizing adaptive window control strategies. However, it is not clear if a simpler feedback system can be developed by leveraging on BIM signalling systems and, in particular, if these systems can be effective in schools.

This paper explores the integration of IoT sensor data into Building Information Modeling (BIM) frameworks using visual scripting techniques to support data-driven decision-making for optimizing indoor environmental quality in schools. A key component of this approach is an IoT-based window signaling system that provides real-time feedback to users on optimal window opening times. BIM calculates these times using a simple ventilation model to ensure compliance with *Criteri Ambientali Minimi* (CAM) - "Minimum Environmental Criteria" - air quality requirements. The model's output determines the recommended window opening duration, which is then communicated to the IoT system to guide manual ventilation control. The effectiveness of this method is demonstrated through a case study conducted in a school in Rome, Italy to answer the following research questions: (i) Are the air change rates prescribed by standards sufficient to maintain indoor air quality and thermal comfort when evaluated using simple calculation models?; (ii) Can the integration of IoT sensor systems and user interfaces into the BIM methodology enhance its effectiveness for dynamic Indoor Environmental Quality (IEQ) control?; (iii) How do students and teachers in an educational setting perceive these systems and the related IEQ?

2 Methods and Materials

The methodology is structured in 5 phases, as depicted in Fig. 1. First, a BIM model is developed for the case study, derived from integrated survey and archival study (phase 1, "Digital Development"). Then the calculation for compliance check with national regulations is implemented. An IoT sensing toolkit with window signalling system is installed on site and programmed to share data with the BIM (phase 2, "On-site Demonstration"). The optimal window opening times are calculated based on a simplified ventilation model and feedback is provided to the users. The overall system is demonstrated on site and feedback on user perception is collected. A Digital integration between phase 1 and 2 is developed, linking the data coming from the IoT sensing toolkit to the BIM model (phase 3, "Digital Integration).

The main outputs concern both the digital and physical environment: a real-time updated BIM model for IEQ investigation is developed (phase 4) and a comparison between the IEQ values derived from regulations, sensors and perception is elaborated (phase 5).

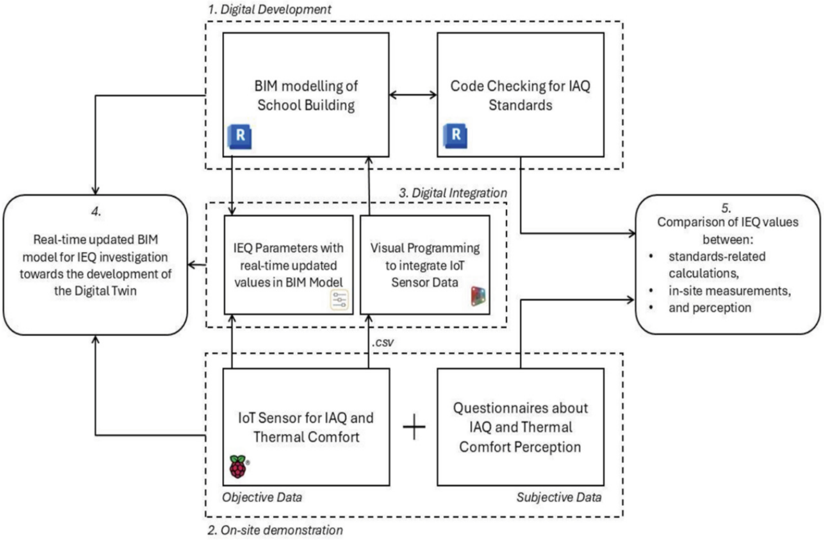


Fig. 1. Workflow of the applied methodology.

2.1 BIM Modeling and Standard Check

The workflow described in Fig. 1 is applied to the case study of Institute Luigi Rizzo in Rome. The school building was already investigated by previous work [18], where an integrated survey with drones and photogrammetry was performed to inform the development of the BIM model (Fig. 2). The study focused on code compliance in two primary areas: thermal comfort and IAQ. Regarding thermal comfort, maintaining appropriate indoor temperatures in schools is essential for students' comfort, well-being, and learning capacity.

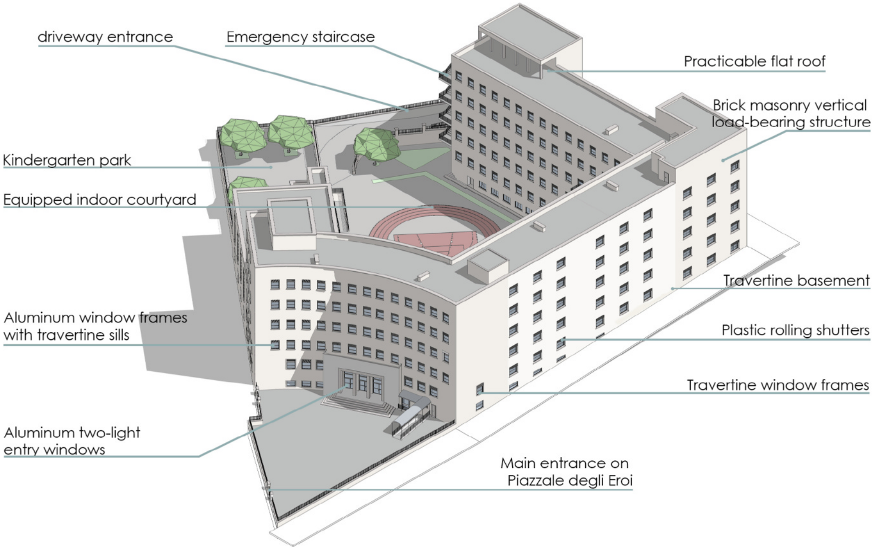


Fig. 2. BIM Model of Istituto Luigi Rizzo [18].

According to Presidential Decree No. 74 of April 16, 2013, and the INAIL study "Safety and Wellbeing in Schools" [19] the ideal temperature ranges for classrooms are 19–22 °C in winter with 40–50% relative humidity and 24–26 °C in summer with 50–60% relative humidity. While not legally binding, these recommendations set the foundations in the aim to achieve comfortable environments.

Requirements for IAQ were derived from relevant regulations, including the CAM Decree of 23rd June 2022 No. 256, which defines "Minimum Environmental Criteria" to promote sustainability in building design and management. This decree establishes ventilation requirements based on outdoor air flow rates per person and per surface area, categorized by building types. For school buildings, the reference values are 7 l/s per person and 0.7 l/s per m^2.

To calculate the effective ventilation flow rate (Q_{eff}), the study considered wind speed, window design, and fixture characteristics. Meteorological data from two nearby stations (IROME7740 and IROME7735) were used to estimate wind speeds at different building elevations, applying correction factors based on UNI 9494-1:2017 standards for casement windows with a 30° opening angle.

Automation tools within the BIM Authoring software Autodesk Revit facilitated the calculation of Q_{eff} (Fig. 3). A comparison was made between the actual ventilation flow rate and the CAM 2022 regulatory requirements. Additionally, the automation process determined the optimal "window opening time" to achieve complete air exchange (Eq. 1), ranging from 5 to 8 min per hour, ensuring compliance with IAQ standards while minimizing classroom disruption.

$$Window\ opening\ time = \frac{QrCAM}{Qeff} = \frac{Qp + Qs}{Qeff} \tag{1}$$

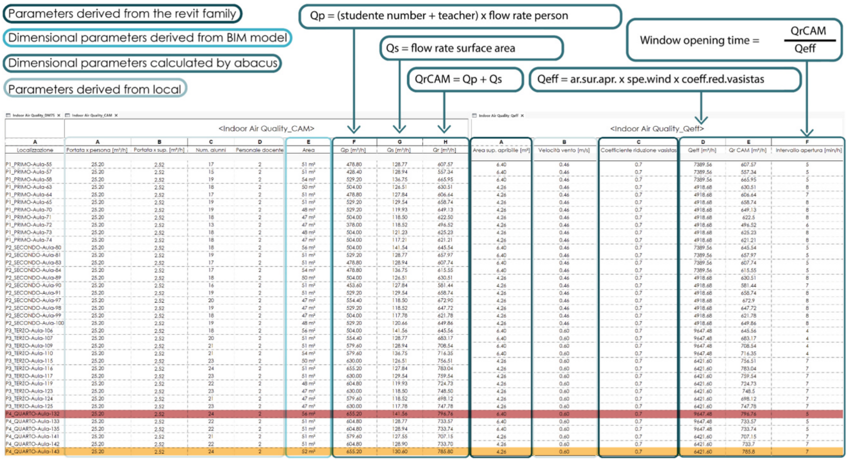
where:

$$Qp = (n.students + n.teachers) \times flow\ rate\ person$$

$$Qs = flow\ rate\ room\ surface\ area$$

$$Qeff = opening\ surface\ area \times wind\ speed \times coeff\ window\ type$$

The Window opening time is calculated as the ratio between the Qr and Qeff. Two classrooms were selected to test the sensor: classroom 1 (i.e. number 3A) and classroom 2 (number 3B). They are located on the 4th floor of the building and we differentiate expositions (Fig. 4).



<Indoor Air Quality_CAM>

A	A	B	C	D	E	F	G	H
Localizzazione	Portata x persona [m³/h]	Portata x sup. [m³/h]	Num. alunni	Personale docente	Area	Qp [m³/h]	Qs [m³/h]	Qr [m³/h]
P1_PRIMO-Aula-55	25.20	2.52	17	2	51 m²	478.80	128.77	607.57
P1_PRIMO-Aula-57	25.20	2.52	15	2	51 m²	428.40	128.94	557.34
P1_PRIMO-Aula-58	25.20	2.52	19	2	54 m²	529.20	136.75	665.95
P1_PRIMO-Aula-63	25.20	2.52	18	2	50 m²	504.00	126.51	630.51
P1_PRIMO-Aula-64	25.20	2.52	17	2	51 m²	478.80	127.84	606.64
P1_PRIMO-Aula-65	25.20	2.52	19	2	51 m²	529.20	129.54	658.74
P1_PRIMO-Aula-70	25.20	2.52	19	2	48 m²	529.20	119.93	649.13
P1_PRIMO-Aula-71	25.20	2.52	18	2	47 m²	504.00	118.50	622.50
P1_PRIMO-Aula-72	25.20	2.52	13	2	47 m²	378.00	118.52	496.52
P1_PRIMO-Aula-73	25.20	2.52	18	2	48 m²	504.00	121.23	625.23
P1_PRIMO-Aula-74	25.20	2.52	18	2	47 m²	504.00	117.21	621.21
P2_SECONDO-Aula-80	25.20	2.52	18	2	56 m²	504.00	141.54	645.54
P2_SECONDO-Aula-81	25.20	2.52	19	2	51 m²	529.20	128.77	657.97
P2_SECONDO-Aula-83	25.20	2.52	17	2	51 m²	478.80	128.94	607.74
P2_SECONDO-Aula-84	25.20	2.52	17	2	54 m²	478.80	136.75	615.55
P2_SECONDO-Aula-89	25.20	2.52	18	2	50 m²	504.00	126.51	630.51
P2_SECONDO-Aula-90	25.20	2.52	16	2	51 m²	453.60	127.84	581.44
P2_SECONDO-Aula-91	25.20	2.52	19	2	51 m²	529.20	129.54	658.74
P2_SECONDO-Aula-97	25.20	2.52	20	2	47 m²	554.40	118.50	672.90
P2_SECONDO-Aula-98	25.20	2.52	19	2	47 m²	529.20	118.52	647.72
P2_SECONDO-Aula-99	25.20	2.52	18	2	47 m²	504.00	117.78	621.78
P2_SECONDO-Aula-100	25.20	2.52	19	2	48 m²	529.20	120.66	649.86
P3_TERZO-Aula-106	25.20	2.52	18	2	56 m²	504.00	141.56	645.56
P3_TERZO-Aula-107	25.20	2.52	20	2	51 m²	554.40	128.77	683.17
P3_TERZO-Aula-109	25.20	2.52	21	2	51 m²	579.60	128.94	708.54
P3_TERZO-Aula-110	25.20	2.52	21	2	54 m²	579.60	136.75	716.35
P3_TERZO-Aula-115	25.20	2.52	23	2	50 m²	630.00	126.51	756.51
P3_TERZO-Aula-116	25.20	2.52	24	2	51 m²	655.20	127.84	783.04
P3_TERZO-Aula-117	25.20	2.52	23	2	51 m²	630.00	129.54	759.54
P3_TERZO-Aula-119	25.20	2.52	22	2	48 m²	604.80	119.93	724.73
P3_TERZO-Aula-123	25.20	2.52	23	2	47 m²	630.00	118.50	748.50
P3_TERZO-Aula-124	25.20	2.52	21	2	47 m²	579.60	118.52	698.12
P3_TERZO-Aula-125	25.20	2.52	23	2	47 m²	630.00	117.78	747.78
P4_QUARTO-Aula-132	25.20	2.52	24	2	56 m²	655.20	141.56	796.76
P4_QUARTO-Aula-133	25.20	2.52	22	2	51 m²	604.80	128.77	733.57
P4_QUARTO-Aula-135	25.20	2.52	22	2	51 m²	604.80	128.94	733.74
P4_QUARTO-Aula-141	25.20	2.52	21	2	51 m²	579.60	127.55	707.15
P4_QUARTO-Aula-142	25.20	2.52	22	2	51 m²	604.80	128.90	733.70
P4_QUARTO-Aula-143	25.20	2.52	24	2	52 m²	655.20	130.60	785.80

<Indoor Air Quality_Qeff>

A	B	C	D	E	F
Area sup. apribile [m²]	Velocità vento [m/s]	Coefficiente riduzione vasistas	Qeff [m³/h]	Qr CAM [m³/h]	Intervallo apertura [min/h]
6.40	0.46	0.7	7389.56	607.57	5
6.40	0.46	0.7	7389.56	557.34	5
6.40	0.46	0.7	7389.56	665.95	5
4.26	0.46	0.7	4918.68	630.51	8
4.26	0.46	0.7	4918.68	606.64	7
4.26	0.46	0.7	4918.68	658.74	8
4.26	0.46	0.7	4918.68	649.13	8
4.26	0.46	0.7	4918.68	622.5	8
4.26	0.46	0.7	4918.68	496.52	6
4.26	0.46	0.7	4918.68	625.23	8
4.26	0.46	0.7	4918.68	621.21	8
6.40	0.46	0.7	7389.56	645.54	5
6.40	0.46	0.7	7389.56	657.97	5
6.40	0.46	0.7	7389.56	607.74	5
6.40	0.46	0.7	7389.56	615.55	5
4.26	0.46	0.7	4918.68	630.51	8
4.26	0.46	0.7	4918.68	581.44	7
4.26	0.46	0.7	4918.68	658.74	8
4.26	0.46	0.7	4918.68	672.9	8
4.26	0.46	0.7	4918.68	647.72	8
4.26	0.46	0.7	4918.68	621.78	8
4.26	0.46	0.7	4918.68	649.86	8
6.40	0.60	0.7	9647.48	645.56	4
6.40	0.60	0.7	9647.48	683.17	4
6.40	0.60	0.7	9647.48	708.54	4
6.40	0.60	0.7	9647.48	716.35	4
4.26	0.60	0.7	6421.60	756.51	7
4.26	0.60	0.7	6421.60	783.04	7
4.26	0.60	0.7	6421.60	759.54	7
4.26	0.60	0.7	6421.60	724.73	7
4.26	0.60	0.7	6421.60	748.5	7
4.26	0.60	0.7	6421.60	698.12	7
4.26	0.60	0.7	6421.60	747.78	7
6.40	0.60	0.7	9647.48	796.76	5
6.40	0.60	0.7	9647.48	733.57	5
6.40	0.60	0.7	9647.48	733.74	5
4.26	0.60	0.7	6421.60	707.15	7
4.26	0.60	0.7	6421.60	733.7	7
4.26	0.60	0.7	6421.60	785.8	7

Fig. 3. Code Checking on air quality and air exchange aspects within Autodesk Revit [18]. In red and yellow the two classrooms selected for the demonstration.

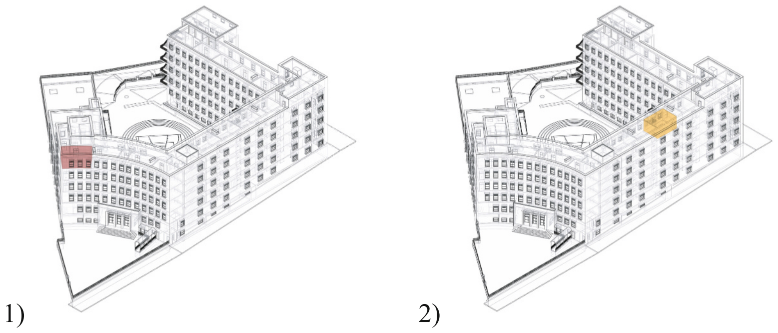

1) 2)

Fig. 4. Classroom1 (in red) and 2 (in yellow) location within the school building.

Table 1. Components of the IoT toolkit for window signalling systems.

Component	Function	Precision	Range
Raspberry Pi 4	Controls the signaling system, processes sensor data, and manages communication with the BIM model	N/A	N/A
WS2812 RGB	Displays red or green light to indicate whether the window position is correct	N/A	N/A
COZIR-LP-5000	Measures indoor temperature, humidity, and CO_2 levels	Temperature: ± 0.1 °C Humidity: ± 2%RH CO_2: ± 50 ppm or ± 3% of reading (whichever is greater)	Temperature: –10 °C to 60 °C / Humidity: 0% to 95%RH / CO_2: 0 to 5,000 ppm
Sensirion SEN50-SDN-T	Monitors particulate matter ($PM_{1.0}$, $PM_{2.5}$, $PM_{4.0}$, PM_{10}), outdoor temperature, and humidity	PM1.0 & PM2.5: 0–100 $\mu g/m^3$: ± 5 $\mu g/m^3$ 100–1,000 $\mu g/m^3$: ± 10% PM4 & PM10: 0–100 $\mu g/m^3$: ± 25 $\mu g/m^3$ 100–1,000 $\mu g/m^3$: ± 25% Temperature: ± 0.5 °C Humidity: ± 0.5%RH	PM: 0 to 1,000 $\mu g/m^3$ / Temperature: –10 °C to 60 °C / Humidity: 0% to 100%RH
Magnetic Switch	Detects whether the window is open or closed	N/A	N/A

2.2 IoT Sensors for IAQ and Thermal Comfort

The Window Signaling System was developed using a Raspberry Pi 4, to which four components were wired: a WS2812 RGB LED strip, an indoor sensor, an outdoor sensor, and a contact sensor. These components are described in Table 1.

The LED strip served as a visual indicator for window position compliance, displaying green (Fig. 5) when the window was correctly positioned and red (Fig. 5.2) when it was not. The indoor environment was monitored using the COZIR-LP-5000 sensor (Fig. 5.3), which measures temperature, humidity, and CO$_2$ levels. The outdoor conditions were assessed with the Sensirion SEN50-SDN-T sensor (Fig. 5.4), capturing particulate matter concentrations (PM$_{1.0}$, PM$_{2.5}$, PM$_{4.0}$, PM$_{10}$), as well as temperature and humidity. A contact sensor (Fig. 5.5) installed on the window detected its open or closed state. The system was integrated with a BIM model via an online server, retrieving scheduled window operation times. It ran two continuously operating programs: (1) a data logging system that recorded sensor data every minute, and (2) a control algorithm that determined the required window position per hour and adjusted the LED strip accordingly.

Fig. 5. Window Signaling System IoT Sensor: (1) LED Strip - green light; (2) LED Strip - red light; (3) COZIR-LP-5000 sensor; (4) SEN50-SDN-T sensor; (5) contact sensor. (Color figure online)

2.3 Children's Perception of IAQ and Thermal Comfort

A questionnaire was designed to assess the perception of indoor thermal and air quality, and satisfaction with the window signalling system. The questionnaire was distributed in two phases. The first time was during the pre-intervention phase, when participants were asked to rate the frequency in which they experience discomfort and their level of satisfaction with the indoor environmental quality in the classroom, including temperature changes, thermal discomfort, wind/draught, unpleasant smells, excessive sunlight, and inadequate lighting. For each item, respondents chose from four response options—"Yes," "Often," "Sometimes," and "No"—which reflect the frequency or intensity of their discomfort, following the approach [20]. In the post-intervention phase, the questionnaire was modified to evaluate whether the system had helped to alleviate these comfort issues, with the same set of items and response categories. This consistent design across pre- and post-intervention questionnaires ensured that any observed changes in responses could be directly attributed to the intervention.

The data from the two classrooms is compared (e.g., classroom 1 and classroom 2) and by time (Pre-intervention vs. Post-Intervention), and descriptive statistics (mean and standard deviation) were computed. Due to the ordinal and non-normal nature of the data, non-parametric Mann–Whitney U tests were employed to compare pre- and post-intervention responses, with significance at $p < 0.05$.

2.4 BIM Visual Programming, Parametric Modeling and IoT for IEQ

The digital integration phase (phase 3) was developed using two different processes that allow an extension of the potential of BIM information modeling. On the one hand, there is visual programming, developed using Dynamo in the Revit environment. The proposed workflow consists of three main stages. First, data is imported into Autodesk Revit through Dynamo, a visual programming tool that facilitates the integration of external datasets. Specifically, a.csv file, which is continuously updated in real-time based on sensor input and predefined temporal granularity, is imported into Dynamo. This allows for the dynamic acquisition of relevant data. Second, the extracted data is assigned to the corresponding Revit family parameters. By employing an appropriate sequence of nodes within Dynamo, the numerical values - such as environmental parameters - or categorical inputs, such as the binary state of window openings (yes/no), are automatically inserted into the designated room parameters in Revit. Lastly, the collected data can be visualized through graphical representations within the Revit environment. By utilizing a structured node sequence, time-series plots of the recorded data are generated and updated continuously. Additionally, Revit enables the preservation of historical data within a user-defined time interval, ensuring that past values remain accessible for further analysis.

On the other hand, parametric modeling through a specific plug-in to insert parameters related to IEQ aspects into the model. The methodology employed the ParaManager function of the DiRootsOne 2.1.3 plug-in for parametric modeling within the research workflow. This tool was utilized to integrate parameters related to Indoor Environmental Quality (IEQ), specifically focusing on CO_2 concentration, temperature, humidity, and particulate matter (PM). By leveraging ParaManager, the defined IEQ parameters were systematically incorporated into the Revit project environment, enabling a structured connection between technological and environmental system elements. This approach facilitated the seamless management and automation of parameter data to support the research objectives.

The actual values of the individual parameters were then inserted into the BIM model through a special dynamo script that connected it to the sensor, making the model always updated with the values of the indicated quantities that automatically change every 15 min.

2.5 Experimental Procedure

The experiment was conducted on two third-grade classes located on the fourth floor of the building, in which there were respectively 19 students and 4 teachers (classroom 1) and 17 students and 1 teacher (classroom 2). Both classrooms are equipped with 3 windows, divided horizontally into three parts, of which the opening parts are only the one at the base and the one at the top, and they open only to vasistas. The classrooms have different surface measurements: classroom1 measures 56 m^2, while classroom 2 measures 52 m^2.

The measurements were conducted for two days in each classroom in the month of January, therefore considering a winter climate and the heating system on.

The Window Signaling System was installed in the corner of the classroom and its operation was explained to the students and teachers at the beginning of the first day of class (Fig. 6). The system LED was set to turn red whenever an action is required by the user, while it turns green when no operations are required. The time of opening the windows to ensure a complete exchange of internal air was calculated as explained in Subsect. 2.1 and was set in the sensor system (5 min for class1; 7 min for class2). The sensor transmitted the data in real time and every hour the LED turned red to ask the user to open the window, once opened the LED turned green, after which it turned red again after the minutes necessary for the air exchange. After explaining how the sensor worked, the questionnaire on behaviors and perceptions was administered to students and teachers. In both classrooms, lessons took place from 8.00 to 14.00.

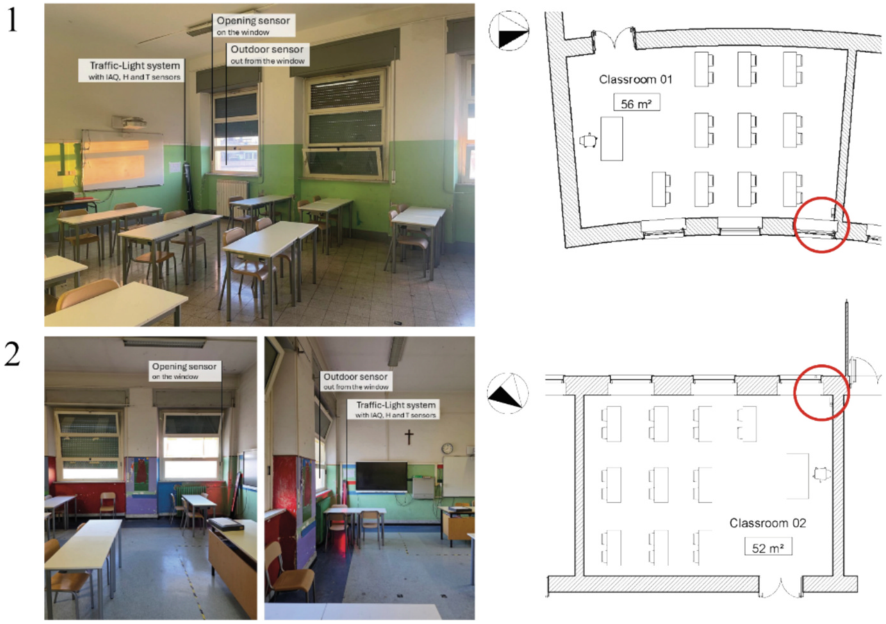


Fig. 6. Classroom 1 and classroom 2 setup and sensor placement. The red circle indicates the sensor's location in the classroom.

3 Results

The research results are presented following the methodology in par.2. First of all, the results of the field experimentation on objective (Subsect. 3.1) and subjective (3.2) data are reported. Then follow the results of phase 3 of digital integration (3.3) in which a BIM model updated in real time is defined towards a use as a Digital Twin (3.4). To conclude with the comparison between calculated data and measured data (3.5).

3.1 IoT Sensors for IAQ and Thermal Comfort

Table 2 shows the average, minimum and maximum time for each hour when windows were left open in both classrooms. According to the computed ventilation time, open window time was supposed to be equivalent to 7 min while for classroom 2 is 5 min. Overall, the average time was approximately close to the recommended interval, in particular classroom 1 had a slightly lower average time while classroom 2 slightly higher.

Table 2. Window opening time for each classroom, average, minimum and maximum time for each hour.

Classroom	Average window opening time per hour (min)	Minimum opening time per hour (min)	Maximum opening time per hour (min)
Classroom 1	6,5	4	7
Classroom 2	5,9	5	22

As shown in Fig. 7, students across both classrooms perceived an increase in window-opening frequency over time. Specifically, they reported that windows were more frequently opened once per hour following the installation of the window signaling system. As shown in Fig. 8, windows were generally open by both students and teachers in both the pre and the post intervention scenario.

The human-window interaction influenced by the window signaling system impacted indoor environmental quality and perception by increasing the duration for which windows remained open. Figure 9 illustrates the temporal evolution of CO_2 concentration levels, showing that longer window openings led to a reduction in CO_2 levels. However, despite these extended periods of ventilation, the total window opening time remained insufficient to consistently maintain CO_2 concentrations below the recommended threshold. Although there is no regulated threshold value in Italy, the note from the National Institute of Health reports a guide value of 1000 ppm of CO_2 as a threshold for indoor environments [21]. This is an average value over the sampling period of an 8-h working day. The monitored value in classroom 2 is approximately 1000 ppm, while in classroom 1 this value is exceeded (Fig. 10).

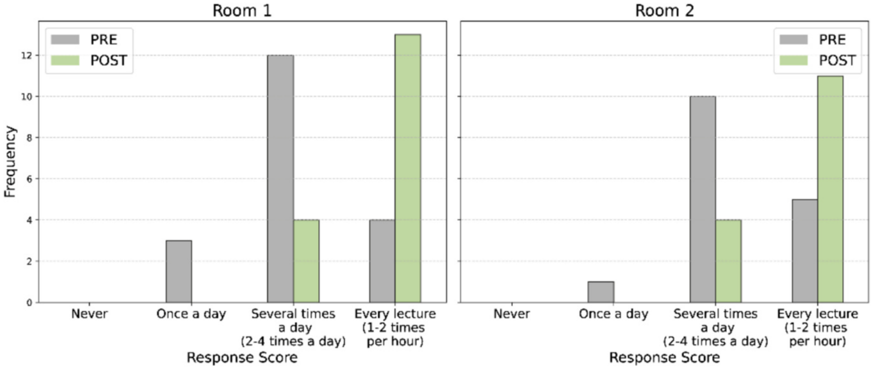


Fig. 7. Perceived frequency of window opening as reported by the students.

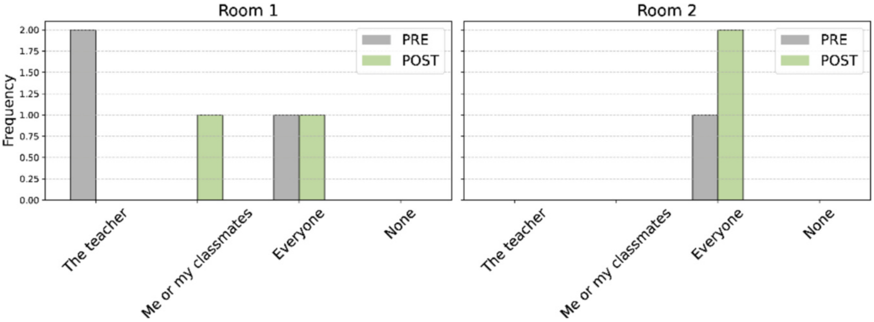


Fig. 8. Perceived actor interacting with the window from students perception.

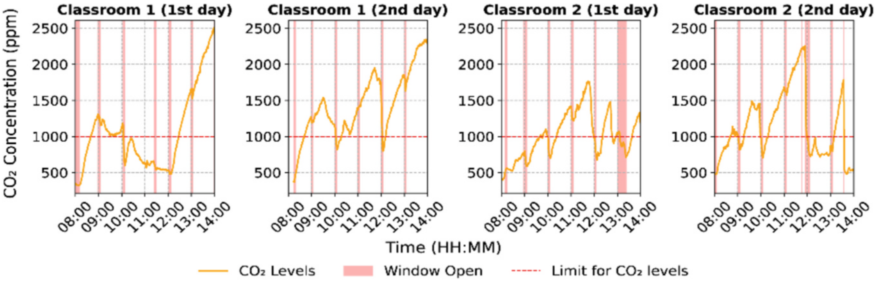


Fig. 9. Temporal evolution of CO_2 concentration levels indoor with indication of recommended maxim limits, and intervals in which the window was open. Red strips show the time window was open. (Color figure online)

As shown in Fig. 11, since the implemented system did not account for indoor $PM_{2.5}$ or PM_{10} concentrations, windows were sometimes opened when outdoor PM levels exceeded recommended thresholds.

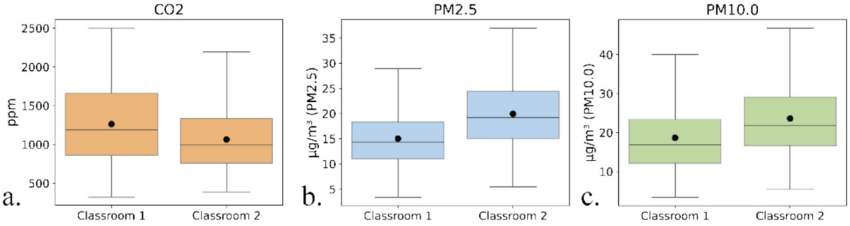


Fig. 10. Distribution of CO_2 concentration levels (a), PM2.5 (b), PM10 (c). Median is indicated with a black line, while the mean with a black dot. (Color figure online)

This highlights the importance of integrating both indoor and outdoor PM monitoring in IAQ evaluation and dynamic control strategies to optimize ventilation while minimizing exposure to particulate matter.

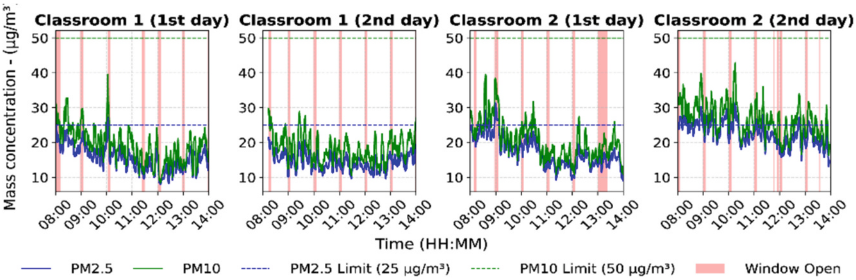


Fig. 11. Temporal evolution of PM concentration levels outdoor with indication of recommended maximum limits, and intervals in which the window was open. Red strips show the time window was open. (Color figure online)

In terms of indoor air temperature, the window signaling system and increased window opening times did not compromise thermal comfort, as temperatures consistently remained within the recommended range of 19–22 °C (Figs. 12 and 13). However, sensor data also indicated both a limited number of hours were air temperatures were below the minimum comfort level of 19 °C. In addition, a slight overheating, with air temperatures exceeding 22 °C for several hours, was observed. A notable exception occurred on the second day of intervention in Classroom 2, where a significant temperature drop was observed. Given the brief duration of window openings during that period, other factors—rather than ventilation alone—are likely to have influenced this decrease. Additionally, the first graph on the left shows excessive overheating, which may be attributed to the sensor's proximity to a radiator or exposure to solar radiation.

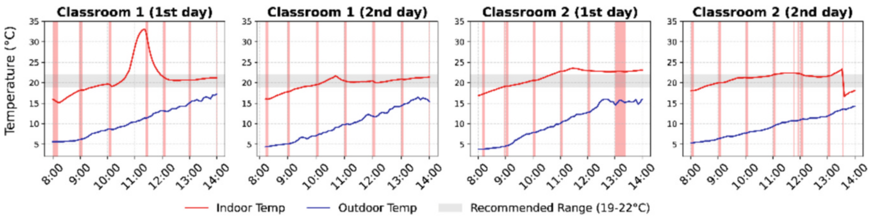


Fig. 12. Temporal evolution of air temperature values in both classrooms during the days in which the window signalling system was in operation. Monitoring was conducted between 08:00–14:00 h. Red strips show the time window was open. (Color figure online)

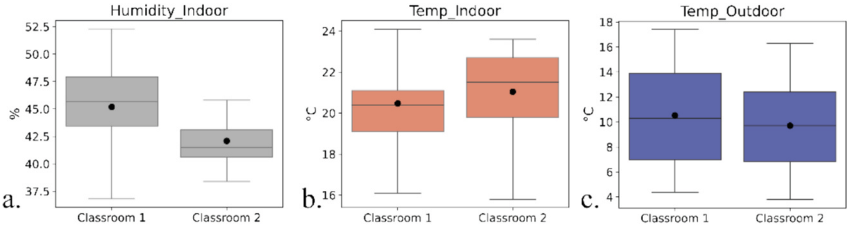


Fig. 13. Distribution of indoor humidity (a), indoor air temperature (b) and outdoor air temperature (c).

3.2 Children's Perception of IAQ and Thermal Comfort

Table 3 and Fig. 14 shows children's perceptions of different indoor environmental factors before and after an intervention. The mean and standard deviation are reported for both pre- and post-intervention conditions, with p-values indicating the statistical significance of the differences between them (Table 3).

In Room 1, the only statistically significant change was observed for lighting, with ratings increasing from 0.20 pre-intervention to 0.54 post-intervention ($p < 0.01$), while temperature changes, thermal discomfort, and wind/drafts showed no significant differences; moreover, smells remained virtually unchanged (0.80 pre vs. 0.81 post).

In Room 2, thermal discomfort significantly improved, decreasing from 0.52 pre-intervention to 0.23 post-intervention ($p = 0.03$), whereas temperature changes, wind/drafts, sunlight, and lighting did not differ significantly, and smells exhibited a non-significant decrease from 0.52 to 0.42.

Finally, the questionnaires included questions for both teachers and students regarding their satisfaction with the window signaling system (Fig. 15). Regarding perceived distraction (Fig. 15a), the majority of students and teachers did not find the system disruptive, with the exception of a few students in Classroom 2 who reported some level of distraction.

In terms of willingness to continue using the system, responses varied between the two classrooms (Fig. 15b). In Classroom 1, both students and teachers expressed a positive attitude, indicating agreement with continuing its use. In contrast, in Classroom 2, students reported a neutral stance (neither agreeing nor disagreeing), while teachers opposed its continued implementation. This discrepancy highlights the highly contextual

Table 3. Children's perceptions of different indoor environmental factors before and after an intervention.

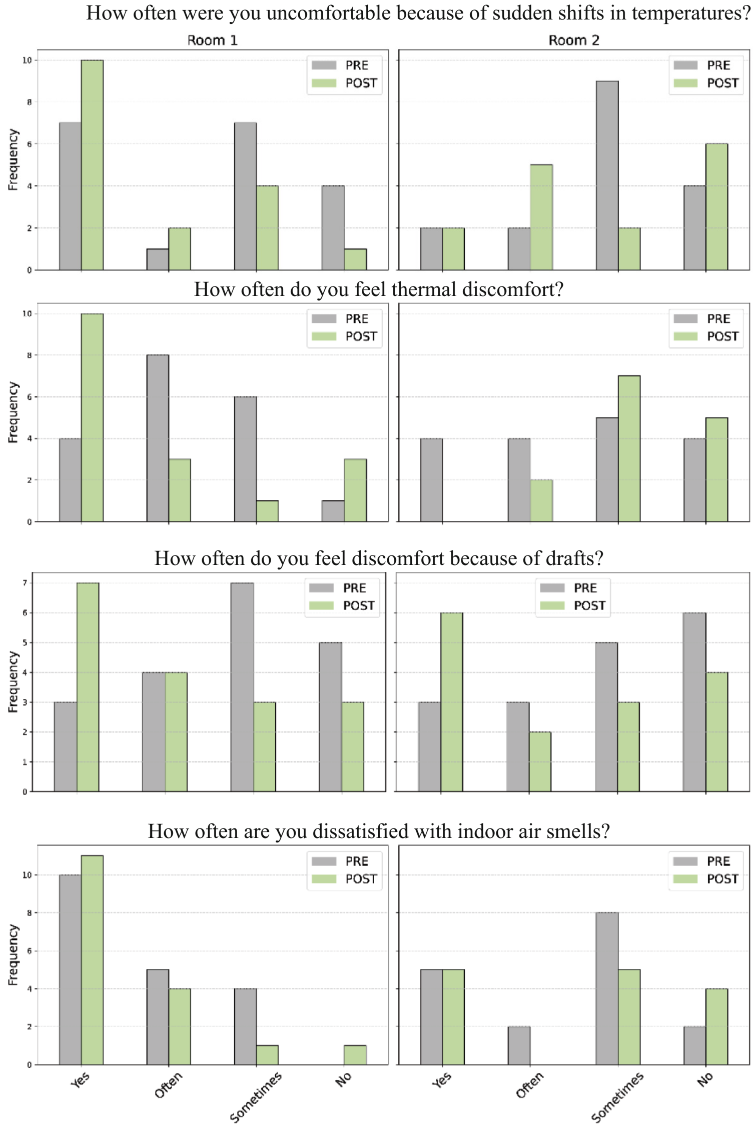
Room	Are you bothered by?	Pre-Intervention Mean (std)	Post-Intervention Mean (std)	p-value	Significant ($p < 0.05$)
1	Temperature changes	0.48 (0.40)	0.72 (0.34)	0.06	No
1	Thermal discomfort	0.59 (0.27)	0.70 (0.38)	0.15	No
1	Wind/drafts	0.45 (0.35)	0.60 (0.38)	0.22	No
1	Smells	0.80 (0.27)	0.81 (0.28)	0.95	No
1	Sunlight	0.32 (0.26)	0.46 (0.42)	0.39	No
1	Lighting	0.20 (0.25)	0.54 (0.39)	< 0.01	Yes
2	Temperature changes	0.41 (0.34)	0.35 (0.38)	0.57	No
2	Thermal discomfort	0.52 (0.38)	0.23 (0.23)	0.03	Yes
2	Wind/drafts	0.43 (0.39)	0.49 (0.44)	0.71	No
2	Smells	0.52 (0.35)	0.42 (0.43)	0.32	No
2	Sunlight	0.35 (0.39)	0.24 (0.35)	0.31	No
2	Lighting	0.24 (0.28)	0.23 (0.33)	0.80	No

nature of smart human-window interaction systems and underscores the importance of their proper handover to final users to ensure alignment with personal needs and preferences.

3.3 BIM Visual Programming, Parametric Modeling and IoT for IEQ

The visual programming and parametric modeling played a pivotal role in integrating IEQ monitoring within a BIM environment. By leveraging Dynamo within Autodesk Revit, a script was developed to integrate real-time sensor data, automate parameter updates, and visualize time-series trends (Fig. 16). The following paragraphs detail the implementation process, from data acquisition and processing to graphical representation and integration within the BIM model.

The initial step in the script involves linking the sensor data to Revit for real-time updates (Fig. 16.1). This is achieved through a.csv file that continuously receives and stores sensor readings. The data is imported into Dynamo using the "File Path" node, which specifies the location of the file, and the "FileSystem.ReadText" node, which extracts the textual content. At this stage, the imported data exists as raw text and requires further processing to be structured appropriately for visualization and parameter assignment. Data cleaning and formatting are performed using the "String.Split" function to remove empty cells ("\n") and divide in "List" every csv's "Rows" (","), followed by "List.RestOfItems" to segment the values into discrete elements (Fig. 17).


How often were you uncomfortable because of sudden shifts in temperatures?

How often do you feel thermal discomfort?

How often do you feel discomfort because of drafts?

How often are you dissatisfied with indoor air smells?

Fig. 14. Children's perceptions of different IEQ factors before and after an intervention.

Subsequently, the "List.Transpose" node is used to organize the extracted values into distinct lists based on data categories. Each resulting list corresponds to a specific parameter in the csv, which can then be individually selected using the "List.GetItemAtIndex" node. Once the sensor data has been categorized and structured, the next phase involves updating the relevant Revit parameters and visualizing the temporal variation of the recorded values. In this case, the data covers a typical school day from 08:00 to 14:00. To generate a graphical representation of the recorded measurements, two curves are

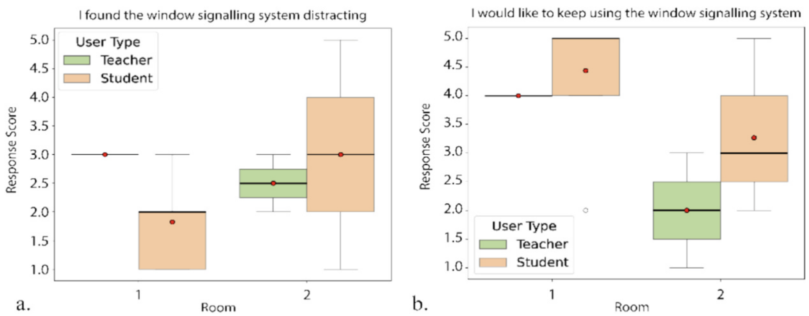


Fig. 15. Level of agreement with sentences regarding perception of window signalling system of students and teachers, from 1 "I disagree" to 5 "I agree": a. I found the window signalling system distracting; b. I would like to keep using the window signalling system.

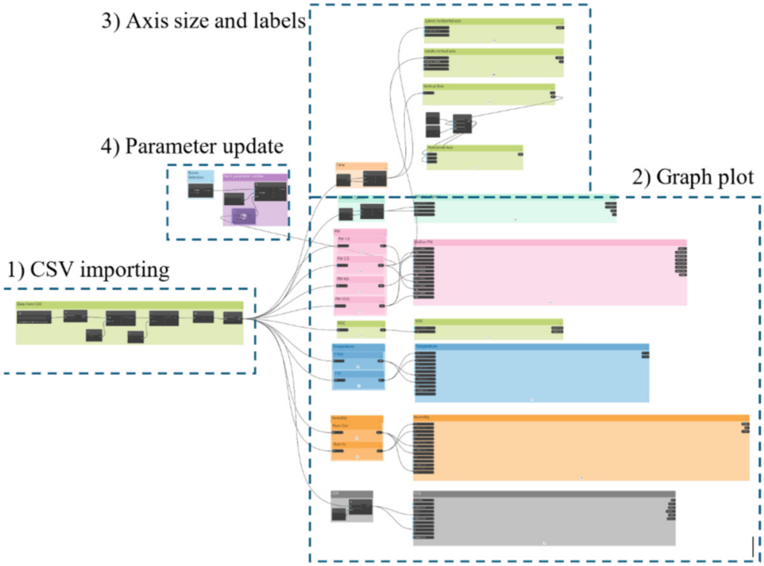


Fig. 16. Dynamo script to integrate real-time sensor data (1), visualize time-series trends (2–3), and automate parameter updates (4).

defined to establish the upper boundary (sensor data values) and the lower boundary (X-axis). The "Point.ByCoordinates" node is used to plot data points where the X-values correspond to the number of recorded measurements, calculated using the "List.Count" function, while the Y-values represent the processed sensor readings extracted via the "List.GetItemAtIndex" node.

To integrate the generated visual elements into Revit, the graphical geometries created in Dynamo must be transferred to the BIM model. This is accomplished by converting the two plotted curves into a surface using the "Surface.ByLoft" node (Figs. 16.2–18). The resulting surface geometry is then imported into Revit through

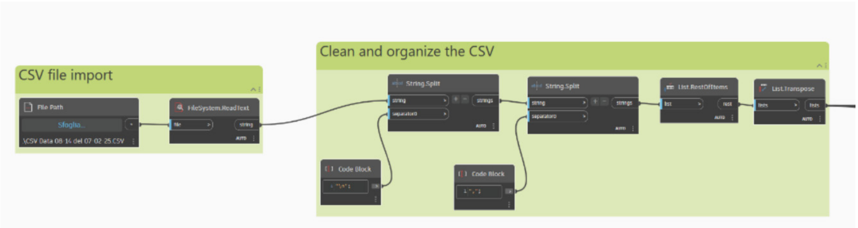
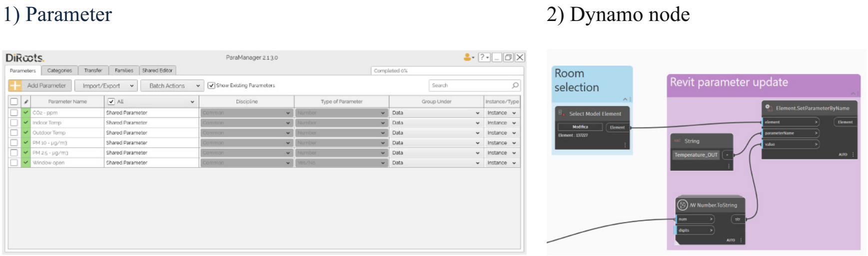


Fig. 17. Dynamo script to integrate real-time sensor data.

the "ImportInstance.ByGeometry" node and can be further customized using the "Element.OverrideColorInView" node to enhance visual distinction. The axis and label color nodes (Fig. 16.3) were used as graphical graphic adjustments for the most suitable representation of sensor data.

Fig. 18. Dynamo script to visualize time-series trends of sensor data.

To ensure a structured and consistent integration of IEQ-related parameters within the BIM model, also a parametric modeling approach was employed using DiRoots ParaManager®. This plugin facilitated the creation and management of custom parameters, in this case tailored to the specific requirements of IEQ monitoring. New parameters (i.e. indoor temperature, outdoor temperature, CO_2 concentration, $PM_{2.5}$ and PM_{10} concentrations, and window opening status) were defined and assigned to the appropriate Revit elements (i.e. rooms) (Fig. 19). By leveraging this tool, it was possible to establish a standardized parameter set that could be dynamically updated based on real-time sensor data, thereby enhancing the accuracy and usability of the BIM model for environmental analysis.

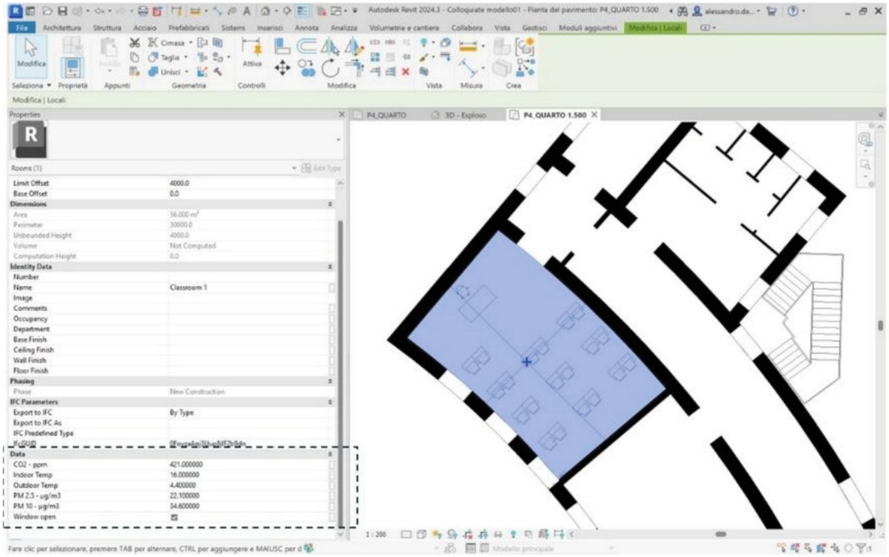


1) Parameter

2) Dynamo node

☐		Parameter Name	☑ All	Discipline	Type of Parameter	Group Under	Instance/Type
☐	✓	CO2 - ppm	Shared Parameter	Common	Number	Data	Instance
☐	✓	Indoor Temp	Shared Parameter	Common	Number	Data	Instance
☐	✓	Outdoor Temp	Shared Parameter	Common	Number	Data	Instance
☐	✓	PM 10 - µg/m3	Shared Parameter	Common	Number	Data	Instance
☐	✓	PM 2.5 - µg/m3	Shared Parameter	Common	Number	Data	Instance
☐	✓	Window open	Shared Parameter	Common	Yes/No	Data	Instance

Fig. 19. Updating process of Revit family parameters using sensor data: DiRoots ParaManager rules (1); Dynamo script to automate parameter updates (2).

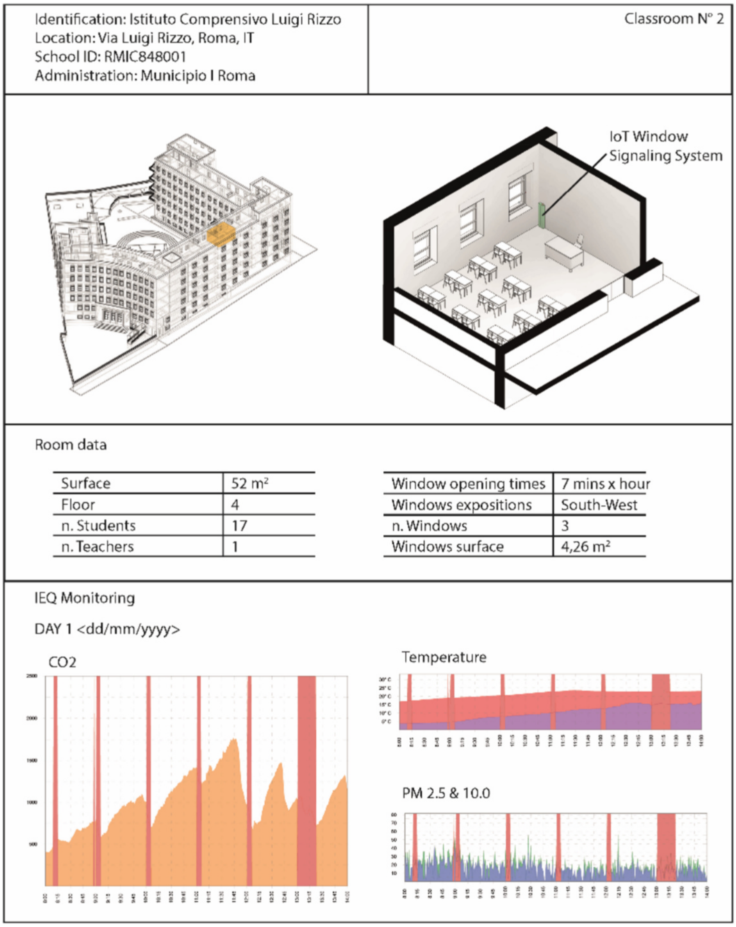


Limit Offset	4000.0
Base Offset	0.0
Dimensions	
Area	56.000 m²
Perimeter	30000.0
Unbounded Height	4000.0
Volume	Not Computed
Computation Height	0.0
Identity Data	
Number	
Name	Classroom 1
Image	
Comments	
Occupancy	
Department	
Base Finish	
Ceiling Finish	
Wall Finish	
Floor Finish	
Phasing	
Phase	New Construction
IFC Parameters	
Export to IFC	By Type
Export to IFC As	
IFC Predefined Type	
IfcGUID	[illegible]
Data	
CO2 - ppm	421.000000
Indoor Temp	16.000000
Outdoor Temp	4.400000
PM 2.5 - µg/m3	22.100000
PM 10 - µg/m3	34.600000
Window open	☑

Fare clic per selezionare, premere TAB per alternare, CTRL per aggiungere e MAIUSC per d

Fig. 20. Revit real-time parameters updated according to sensor measurements.

Figure 19.2 illustrates the process of updating Revit family parameters using sensor data stored in a.csv file in the last Dynamo script node (Fig. 16.4). Specifically, the "Select Model Element" node allows users to choose the "Room" component in which the parameter updates will be applied. The "Element.SetParameterByName" node subsequently assigns the corresponding sensor-derived values to the selected parameter. In the example presented, the "Temperature_OUT" parameter is updated dynamically. This process can be replicated for additional parameters by repeating the same sequence of nodes, ensuring that all relevant environmental data recorded in the.csv file is accurately reflected within the BIM model. Notably, in this case, the data is represented as "text" rather than "numeric" format due to the inclusion of the unit of measurement (°C). The integration process was structured around two key components: the continuous update of BIM parameters (Fig. 20) and the visualization of time-series data (Fig. 21). The updated parameters were then visualized directly within the BIM model through automated graphical representations, allowing for the temporal analysis of IEQ variations. Additionally, historical data was preserved within the BIM model, ensuring that past values remained accessible for comparative assessments through a tailored sheet (Fig. 21), printed with the Dynamo script in Fig. 16.



Identification: Istituto Comprensivo Luigi Rizzo
Location: Via Luigi Rizzo, Roma, IT
School ID: RMIC848001
Administration: Municipio I Roma

Classroom N° 2

Room data

Surface	52 m²
Floor	4
n. Students	17
n. Teachers	1

Window opening times	7 mins x hour
Windows expositions	South-West
n. Windows	3
Windows surface	4,26 m²

IEQ Monitoring

DAY 1 <dd/mm/yyyy>

Fig. 21. Revit sheet with Classroom2 monitoring data for day 1.

4 Discussion

Discussions are presented divided into 3 subsections: 4.1 Real-time Updated BIM for IEQ control (toward Digital Twin applications); 4.2 Standard calculation and monitored data comparison; and 4.3 Limitations and future development.

4.1 Real-Time Updated BIM for IEQ Control

The integration of real-time sensor data within the BIM framework enabled the development of an informative digital model that gets continuously updated based on IEQ measurements. This approach facilitated real-time monitoring of key variables such as temperature, CO_2 concentration, and particulate matter ($PM_{2.5}$, PM_{10}), providing an accurate representation of indoor conditions within the BIM environment. As a result, the BIM model evolved into a dynamic representation of the built environment, reflecting real-time variations in environmental conditions and supporting proactive decision-making in IEQ management. This real-time data integration significantly enhanced the BIM model's applicability to Digital Twin methodologies. By continuously synchronizing with measured environmental conditions, the model provided a virtual counterpart of the physical building, allowing facility managers and decision-makers to monitor IEQ performance, assess trends, and implement targeted interventions. The Digital Twin approach also facilitated automated compliance verification, as regulatory or guide values thresholds were directly compared against real-time data within the BIM environment. Furthermore, the system was designed to support IEQ optimization strategies by linking real-time environmental data with building operation parameters. In the specific case of natural ventilation control, the BIM model dynamically adjusted the Window Signaling System based on monitored CO_2 levels and ventilation needs. These aspects are now calculated on standards requirements, but can be upgraded to real-time monitoring values. This integration ensured that occupants received real-time visual feedback on optimal window operation times, thereby enhancing indoor air quality while maintaining energy efficiency. The continuous update mechanism also enabled a more adaptive building management approach, where real-time IEQ conditions could inform operational strategies in educational environments. Moreover, the proposed workflow is an open system that can be implemented with other parameters related to IEQ factors. The real-time updated BIM model demonstrated its effectiveness as a decision-support tool for IEQ management in school buildings. By bridging the gap between static building models and dynamic environmental conditions, this approach facilitated a data-driven methodology for improving indoor comfort, air quality, and overall occupant well-being.

4.2 Air Changes Standard Calculation and Indoor Environmental Quality

A comparative analysis was conducted between standard calculations presented in this paper and the real-time sensor measurements for indoor air temperature and CO_2 concentration in the two monitored classrooms. The objective was to assess whether the mathematically determined ventilation duration was sufficient to maintain indoor environmental conditions within recommended thresholds for occupant health and well-being. The estimated window opening times, derived from a mathematical ventilation model, were evaluated against real-time sensor data to determine their effectiveness in ensuring adequate air exchange and thermal comfort. The mathematical model determined that maintaining optimal indoor temperatures required a window opening duration of 5 min per hour for Classroom 1 and 7 min per hour for Classroom 2. Sensor data collected during the monitoring period confirmed that indoor temperatures generally remained within the recommended range of 19–22 °C, as established by national guidelines for winter conditions. However, Classroom 1 exhibited slight fluctuations, with occasional drops below 19 °C during extended ventilation periods, particularly when external temperatures were lower. In contrast, Classroom 2 demonstrated greater temperature stability, with only minor deviations from the expected range.

For CO_2 concentration, the mathematical model estimated that the prescribed ventilation duration would maintain levels below the recommended threshold of 1000 ppm. Sensor data from Classroom 2 indicated that CO_2 concentrations remained consistently below or near 1000 ppm, confirming the adequacy of the calculated ventilation time. However, in Classroom 1, CO_2 levels frequently exceeded 1000 ppm, particularly in the latter hours of the school day. Peak concentrations surpassed 2500 ppm, indicating that the prescribed ventilation duration was insufficient to prevent CO_2 accumulation under high occupancy conditions. The results suggest that while the calculated ventilation schedule did not have a detrimental effect on thermal comfort, for CO_2 concentration levels and indoor air quality, the prescribed ventilation time was not sufficient in both Classroom 1 and 2. In particular, in Classroom 1, values outside the recommended thresholds were frequently recorded. In Classroom 2, where CO_2 concentrations remained for longer intervals within recommended thresholds, the average window opening duration closely matched the prescribed ventilation time (7 min per hour). However, in Classroom 1, the actual window opening time was frequently shorter than the recommended 5 min, particularly in the later hours of the school day. This discrepancy coincided with the higher CO_2 concentrations observed in Classroom 1, suggesting that deviations from the prescribed ventilation schedule contributed to insufficient air exchange. This finding suggests that additional ventilation measures, such as increased ventilation frequency, higher accuracy air change models or alternative air exchange strategies, may be required to maintain optimal indoor air quality. Increasing the number of air exchanges may also affect user thermal and acoustic comfort, so these parameters should then be integrated more effectively in the control logic of the window signalling system.

Finally, a critical analysis of occupant behavior regarding window operation was conducted to evaluate how students and teachers responded to the window signaling system and whether their actions aligned with the recommended ventilation schedule. The collected data indicate variability in user compliance with the prescribed window opening schedule. Overall, the system led to a higher frequency of human-window interaction. Students in both classrooms generally appreciated the system and did not find it distracting. However, a few teachers in Classroom 2 expressed dissatisfaction, which may be attributed to the system adding an additional task to their responsibilities. The effectiveness of the visual signaling system in prompting window operation was also assessed. In both classrooms, occupants were more likely to open windows in the morning when external temperatures were lower, but compliance decreased throughout the day, particularly after midday. The decline in responsiveness was more pronounced in Classroom 1, where occupants frequently delayed or ignored the signaling system, leading to prolonged periods of inadequate ventilation. Observations suggest that thermal discomfort, external noise, and classroom activities influenced decision-making, with occupants opting to keep windows closed even when the system indicated the need for ventilation. The discrepancy between the calculated ventilation schedule and actual occupant behavior underscores the role of human factors in IEQ management. While the system provided objective guidance for optimal air exchange, adherence was influenced by subjective comfort preferences and external constraints. The findings suggest that additional awareness strategies and adaptive signaling mechanisms may be required to improve user compliance and ensure that indoor air quality is maintained at optimal levels throughout the school day.

4.3 Limitations and Future Developments

Despite the successful integration of real-time sensor data within the BIM environment for Indoor Environmental Quality (IEQ) monitoring, certain limitations must be acknowledged. This pilot study was conducted within a specific climatic and seasonal context (winter conditions) and over a short period, which may limit the generalizability of the findings to other seasons where different ventilation patterns and external environmental factors play a role. Additionally, the study primarily focused on CO_2 concentration and indoor air temperature as key indicators of IEQ. Expanding the scope to include additional parameters such as humidity, particulate matter (PMs), volatile organic compounds (VOCs), and acoustic and soundscape perception could provide a more comprehensive assessment of indoor conditions and occupant responses to the window signaling system. These aspects can be incorporated into the open framework developed in this study and will be considered in future research. In particular, the use of more advanced control algorithms for the window signalling system, which can incorporate both assessments of indoor and outdoor PMs, energy consumption and indoor thermal comfort is recommended.

In terms of future developments, expanding the scope of the BIM-based monitoring system to include multi-building applications could provide valuable insights for large-scale IEQ management in school facilities. Future research should explore the long-term performance and sustainability of BIM-integrated IEQ monitoring systems, assessing their effectiveness across different educational settings and climatic conditions. Conducting multi-seasonal studies and incorporating economic evaluations of energy efficiency versus air quality improvements will be critical for the widespread adoption of such technologies in school environments. From a usability perspective, educational campaigns aimed at increasing occupant awareness of IEQ and its impact on health and cognitive performance could lead to more proactive engagement with ventilation recommendations and system use. The impact of window signalling system on educational outputs should also be considered by future studies, to strike a balance between usability, effectiveness and distraction during the lectures.

5 Conclusions

This study demonstrated the potential of integrating real-time sensor data within a BIM environment to enhance Indoor Environmental Quality (IEQ) monitoring and management in school buildings. By coupling BIM with IoT-based sensing technologies and visual scripting, a continuously updated digital model was developed, enabling real-time assessment of key environmental parameters. The proposed system provided a decision-support tool for school facility management, allowing for more precise interventions to maintain optimal thermal comfort and air quality. The results confirmed that the calculated ventilation schedules were generally effective in maintaining indoor temperatures within the recommended thresholds. However, discrepancies were observed in CO_2 concentration levels, particularly in cases where window opening durations were shorter than prescribed. These findings emphasize the critical role of occupant behavior in ventilation effectiveness, as deviations from the recommended schedule contributed to air quality variations. Beyond the validation of ventilation strategies, this research highlights the applicability of BIM as a dynamic platform for IEQ monitoring, moving toward digital twin applications. The integration of real-time data allowed for automated compliance verification, historical trend analysis, and direct visualization within the digital model, supporting a data-driven and proactive approach to IEQ management. The ability to connect environmental data with building operation parameters represents a significant step forward in adaptive school building management. Future developments should focus on expanding the model to incorporate additional IEQ parameters, such as humidity, particulate matter, and noise levels, and provide a more comprehensive evaluation of indoor conditions through control algorithms that are able to encompass a multi-domain perspective. Additionally, scaling the approach to multi-building applications could offer broader insights into large-scale IEQ management in educational facilities. Conducting multi-seasonal studies will also be crucial in validating the system's adaptability to different climatic conditions. Ultimately, this research demonstrates that BIM-integrated real-time monitoring systems can bridge the gap between static building models and dynamic environmental conditions, fostering healthier, more sustainable, and responsive school environments.

Acknowledgments. Project 2022 - Sapienza University of Rome: SMARTEST "Digital tools for indoor environmental quality in school buildings". Protocol number: RP1221816BF46A04. Scientific referee - PI: Alessandro D'Amico.

Scientific collaboration agreement between the DICEA of the Sapienza University of Rome and the Municipality I of Rome Capital focused on the architecture for education designed and built in Rome from the Unification of Italy to the first thirty years of the twentieth century. Scientific referee: Edoardo Currà.

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