International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Mathematical Modelling of Engineering Problems
Vol. 11, No. 10, October, 2024, pp. 2695-2704
Journal homepage: http://iieta.org/journals/mmep

Integrating Energy Efficiency and Occupancy Control in Shared Public Buildings: A Data-Driven Approach

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https://doi.org/10.18280/mmep.111011

Received: 15 August 2024
Revised: 2 October 2024
Accepted: 8 October 2024
Available online: 31 October 2024

Keywords:
efficiency, environmental monitoring, energy management, IoT, CO_2 sensors

ABSTRACT

Environmental parameter monitoring systems connected in classic Internet of Things (IoT) networks have been evolving in the recent years and are now capable of providing massive amounts of data, that are often accessible to both facility managers and authorized users through smartphone apps. This paper presents an example of such monitoring systems that has been designed to control the environmental data within the many buildings that compose the University of Pisa, with the goal of improving their energy management. In fact, it is known that smart management of the energy system is the best strategy to avoid energy wastes. The topic has become particularly relevant following the COVID-19 pandemic, after mechanical ventilation has been imposed by law in many states. This leads to rather significant increases in energy use, both in the winter and summer seasons. We describe CO_2 monitoring sensors that have been developed at the University of Pisa, based on low-cost components and a secure IoT network, showing their promising potential for energy efficiency applications, also highlighting some shortcomings of currently available technology.

1. INTRODUCTION

Increasing the energy efficiency of buildings is today a fundamental objective in construction, both private and public. Many European articles and projects discuss the construction of new buildings of the ZEB or n-ZEB type [1], and more recently of energy-positive neighborhoods/districts.

To obtain significant environmental results it is necessary on the one hand to redevelop the existing building stock, as proposed in various programs, but also to work on the optimal control of the systems installed in them.

Mechanical systems, such as the heating, ventilation, and air conditioning (HVAC) systems which are used to maintain adequate thermohydrometric and air quality standards in environments, consume 25-50% of the total energy, associated with the management of the buildings themselves [2].

It is therefore clear how the issue of managing mechanical systems is of primary importance to achieve tangible energy savings, which are convenient both in terms of improved energy sustainability, and pragmatically on economic costs.

University buildings, due to their large size, the conspicuous and irregular flows of users and the very differentiated uses of the internal environments - co-presence of classrooms, offices, laboratories - are highly energy intensive systems. It is therefore necessary to also focus attention on their management to achieve energy efficiency in the public building stock. The scientific literature related to optimal building management, provides many examples of theoretical methodologies and practical solutions. For instance, an in-depth study of these issues [3], divides the control methods into two macro-groups: user-defined programs and automatic programs guided by the monitoring of the occupancy of the structure via various sensors and/or meters. It seems quite clear that automatic optimization is significantly better than the manual control by users.

In addition, it is well-known that the efficiency of energy use in buildings heavily depends on the occupancy of the rooms, and on the behavior of the people within the building [4]. At this regard, analyses conducted in the literature have also shown how taking into consideration the actual occupancy of buildings for the management of HVAC systems leads to significant energy savings, estimated at between 30-40% and up to 80% [5]. However, despite the rich literature, it is hard to find such theories adequately translated in practical case studies, also because a single entity may oversee many buildings and structures.

Accordingly, today there is a great development of scientific work regarding environmental monitoring data and the profitable use of these data, both in external and internal environments [6]. The topic of monitoring external environments is of great interest in the field of city security, for example [7]. Especially given that data recorded from cameras suffer from privacy issues, it may be an attractive alternative to use environmental parameters (such as pollution data) as a privacy-preserving alternative. Indeed, the analysis of data measured from motion or CO_2 sensors could be very useful, to provide occupancy information in compliance with privacy regulations. This is a significant change with respect to only a few years ago, when the only application of environmental data was restricted to indoor air quality [8]. This topic, although relevant, does not appear to have been investigated enough in the existing literature. On the other side, restricting the attention to indoor monitoring case studies, environmental monitoring still may be used for a plethora of applications: in the case of healthcare facilities, the functionality may be that of microclimatic control and compliance with safety and health conditions; in other facilities with highly variable occupancy, such as commercial buildings, the aim could be to control the functioning of the energy systems, for example those for heating or cooling and ventilation [9].

University teaching centers of traditional universities fall in the second category, as a considerable energy consumption is associated with their operation. This is especially relevant since the management of HVAC systems in didactic environments is often delegated to external parties that, differently from the didactic centers, do not have particular interest in achieving energy savings [10]. While environmental monitoring may be regarded a dated topic, it has been recently evolving in several directions. One of them, regards the implementation of a suitable IoT network to transmit and share the gathered data. The topic of IoT networks is nowadays largely debated, with energy efficiency purpose too [11, 12].

A true IoT network should be accessible from everywhere in the world, but this may give rise to cyber-security issues. Conversely, local monitoring networks do not suffer from security issues, but accessibility to the data may be limited to the proximity of the building of interest. The debate becomes even more compelling in the case of university centers, as they usually cover very large surfaces and span several buildings – thus appearing more suitable for sharing the same protocol to gather all the measurements in a single web server. However, university centers also handle sensitive data, and special care should be dedicated to address security concerns (Figure 1).

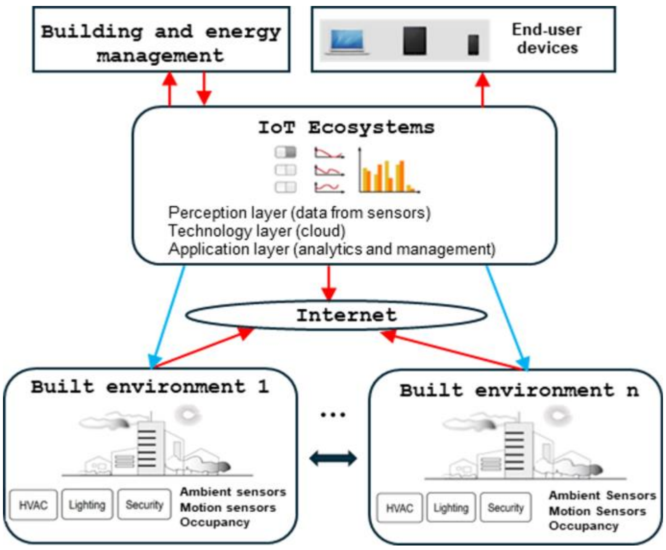

Figure 1. Example the use of IoT Ecosystems for data acquisition in a built environment and feedback

This article explores a series of experiments conducted in shared public structures to assess methods for monitoring environmental parameters, such as temperature, humidity, and CO_2 concentration, with a specific focus on optimal building management and energy savings. Post-COVID 19, the activation of mechanical ventilation in shared public buildings has become crucial, leading to significant energy consumption especially during hot or cold seasons. The collected data can be leveraged to optimize energy efficiency by regulating system usage based on temperature, humidity, and CO_2 concentration level—activating systems only when explicitly necessary and limiting their use during non-essential periods. The article illustrates the structure of a IoT network, and a monitoring system connected to the network with the aim of controlling energy use within the School of Engineering of the University of Pisa.

2. ENERGY EFFICIENCY IN SHARED PUBLIC BUILDINGS: THE CASE OF UNIVERSITY

In recent years, in several European countries including Italy, the drafting of the energy certification of buildings, also called "energy performance certificate" (APE), has become increasingly important. Its objective is the classification of a building based on its energy consumption (in kWh/m^2) through inspections and information provided by the owners of the property. This procedure however only considers the following factors:

-Territorial location, exposure to the sun and climate zone of the building taken into consideration;

-Type of building;

-Stratigraphy of walls, roofs and floors;

-Types of fixtures;

-Type of heating and/or cooling system;

-Presence of renewable sources.

The output of this procedure is the various energy performance indicators (E.P.I) and the energy class of the building, which has the best performance for class A4 and the worst for class G buildings (Figure 2). However, this procedure has major limitations that do not allow an accurate study of the building in its operating conditions. In particular, the management control of air conditioning and/or lighting systems is not considered.

The outputs consider exclusively the general characteristics of the systems and dispersions of the building, which are mainly linked to the walls, fixtures, and climatic conditions of the place where the building is located, but their management is completely neglected.

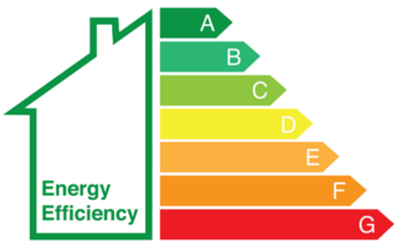

Figure 2. Example of Italian energy certification

The real energy consumption of buildings is different from that calculated in the design phase. This is the biggest limit to achieving effective optimization of plant management.

Only in recent years there has been full awareness of the fact that occupants are mainly responsible for energy consumption: their presence and behavior, depending on the case, are two fundamental variables to consider in the building management model. Therefore, the efficiency of energy use in buildings can only be achieved by integrating the presence/behavior of occupants into the design and management of the systems.

As we have already mentioned, the main use of energy in buildings such as university teaching centers is linked to the operation of air conditioning and ventilation systems.

HVAC systems are systems designed to implement movement treatments on the air, i.e. ventilation, heating and conditioning, cooling, and humidification/dehumidification. The main types of systems are water, all-air and mixed. The latters, thanks to the great flexibility of use, are the most available in structures with large volumes and irregular employment such as university centers. Therefore, the discussion is focused on them, but can still be extended to other types of systems. In relation to the objective of this work it is appropriate to describe the air treatment section in greater detail. It is a complex machine, externally identifiable by a large sheet metal casing, and comprising the following components: dampers for air entry; filters for its sanitization, which cause pressure losses; static crossflow recuperator; heating/cooling battery; dehumidification section; supply and return fans controlled in parallel so that the classrooms are always slightly over pressured compared to the outside. This discussion considers hydronic air handling units (AHUs), where the heat transfer fluid that powers the batteries is water. For example, most of the structures at the University of Pisa have systems like the one shown in Figure 3. These systems can be used for ventilation only or for heating and cooling. The regulation is based on the variation in the flow rate of the air taken from outside and on the return air.

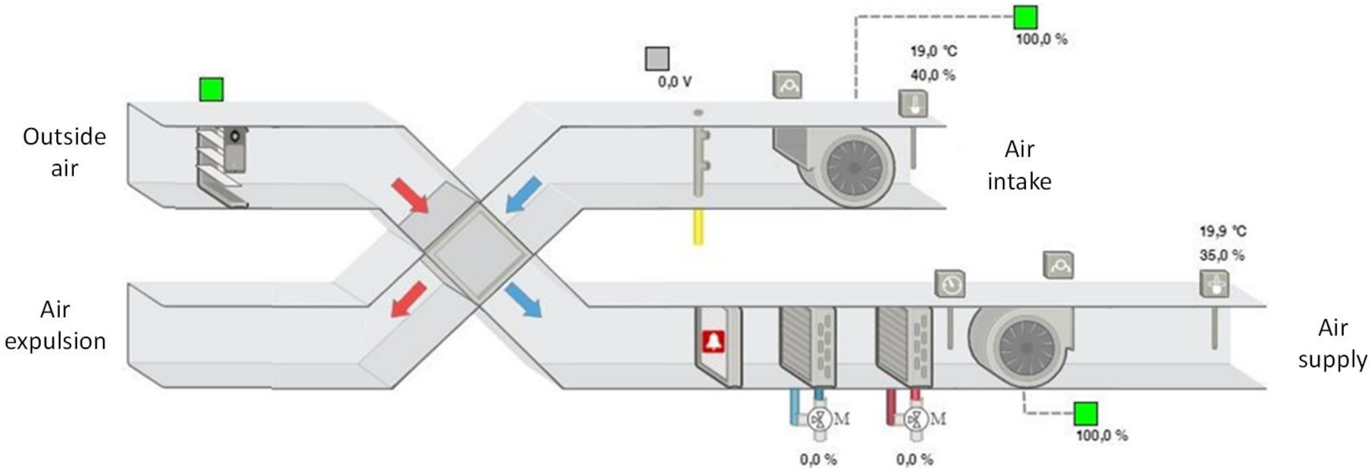

Figure 3. A schematic example of a full-air HVAC plant

In the case of the HVAC air system, like the one represented in Figure 3, the treated air is 100% external and recirculation is not possible, but only heat recovery through the exchanger. It is understandable that these systems, although they allow the best possible air quality in the environment, lead to inevitably higher energy consumption and management costs.

It is possible to understand the connection between the air flow rate and energy uses. Each increase in the flow of air from outside is associated with a proportional increase in power and consequently in energy use. If in the intermediate seasons this is due to the increase in mechanical ventilation (this happens for example in the intermediate seasons when the power is only that of the fan). The power of the fan is by:

$$P_{vent,id} = \frac{\dot{m}\Delta p_{tot}}{\rho} \tag{1}$$

The total pressure losses across the distribution system are divided into two categories. Distributed pressure losses (calculated for both the primary and secondary ducts), caused by dissipation due to viscous effects along the walls of the ducts are due to the dimensions of the ducts and the speed of the air passing through the ducts. Concentrated pressure losses (calculated for both the primary and secondary ducts), due to dissipation in localized discontinuities of the duct, such as bends, narrowing, widenings, valves, etc. Summarizing it is:

$$\Delta p_{tot} = \Delta p_{dist} + \Delta p_{conc} \tag{2}$$

Two efficiencies must be considered: of the inverter, linked to the variation in flow rate compared to the nominal one. In this model, a partialization of the flow rate ranging from 40% to 100% and electric was assumed, linked to the dissipation of energy due to the Joule effect. Therefore, the power absorbed by the fan can be estimated with the equation:

$$P_{vent,real} = \frac{P_{vent,id}}{\eta_{inv} \cdot \eta_{el}} \tag{3}$$

In heating (winter) and cooling (summer) periods the use of energy for ventilation is added to that for heating or cooling,

$$P_{th,heat} = \dot{m} \cdot c_{p,air} \cdot (T_{set-point,loc} - T_{ext}) \tag{4}$$

$$P_{th,cool,id} = \dot{m} \cdot c_{p,air} \cdot (T_{ext} - T_{set-point,loc}) \tag{5}$$

and that for humidification and dehumidification, in this case also this part of the system is active:

$$P_{th,hum} = \dot{m} \cdot \Delta h = \dot{m} \cdot (h_{post-hum} - h_{pre-hum}) \tag{6}$$

$$P_{th,dehum} = \dot{m} \cdot \Delta h = \dot{m} \cdot (h_{pre-dehum} - h_{post-dehum}) \tag{7}$$

Increasing the flow rate of ventilation air the use of energy is increasing and that therefore the flow rate of replacement air must be limited to the quantity necessary and sufficient to maintain environmental healthiness and that any unnecessary replacement will produce an increase of energy consumption associated with the operation of the HVAC system. Just to have an idea of the relevance of the problem, based on the experience gained within the University of Pisa it was possible to understand how much the ventilation heat load weighs on the total consumption, limited to the room heating phase.

From the evaluations reported in Figure 4, referred to real data, it emerges that the share of heat lost through ventilation is just under 46% of the total, while that through transmission is consequently just over 54%.

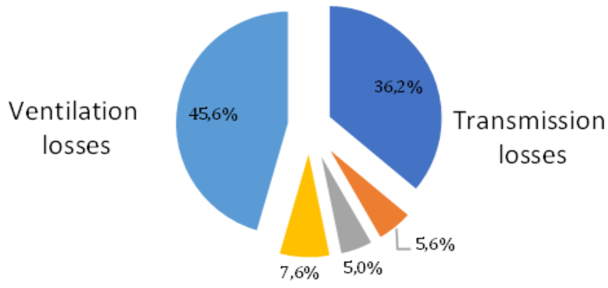

Figure 4. Share of heat lost through ventilation and transmission in HVAC operation

3. OCCUPANCY CONTROL IN PUBLIC BUILDINGS

As was highlighted in the introductory part, the scientific literature is full of studies and analyses on the different methods applicable for managing the control of systems serving the structures to avoid energy wastes.

Table 1. Programs defined by user or system manager

Control Method	Problem/Limitation
Scheduled control	Unnecessary air conditioning during unoccupied hours and excess ventilation during partially occupied hours, leading to relevant waste
Manual or programmed thermostats	Useful only for regulating the operation of any hydronic terminals in small rooms.

Table 2. Methods based on automatic occupancy monitoring

Control Method	Problem/Limitation
Reactive control	Set-point adaptation delay due to system inertia
Predictive control (rule-based control)	Depend on model prediction performance
Predictive control (optimal control)	Depend on model prediction performance and on

The control methods are divided into two macrogroups: programs defined by the user and the manager of the systems themselves and automatic programs guided by the monitoring of the occupancy of the structure via various sensors and/or meters. Tables 1 and 2 summarize the main concepts.

Considering the fixed programs in Table 1, static programs (scheduled control) can in many cases diverge from the real needs of the structure. The mismatch between generation and load demand can cause unnecessary air conditioning during unoccupied hours and excess ventilation during partially occupied hours, leading to extensive waste. On the other hand, manual or programmed thermostats are useful methods only for regulating the operation of any hydronic terminals in small rooms but are not an efficient management method for large buildings, compared to which they lead to little saving or even increased energy expenditure.

Regarding occupancy-based control methods, as those reported in Table 2, this is a type of control that acts according to the information assimilated in real time through the various monitoring systems to dynamically modify the values of the set-point quantities. The performance of these control strategies is in principle the best, but obviously their usefulness is linked to the correctness of the acquired data or models. Reactive control could cause discomfort due to the delay in the set-point adaptation due to the inertia of the system upon the arrival of occupants. Depending on the quantities used to carry out the control. The lag time associated with HVAC systems is the primary limitation. Predictive control strategies are occupancy forecast models based on historical data and developed to create proactive control: by knowing "future" occupancy it is possible to implement appropriate preconditioning of the environments. The performance of predictive control strategies strongly depends on the prediction performance of the model used. The most advanced systems depend on data collection: it is therefore essential to study how the property is used during the 24-hour period.

Precisely to collect data and to carry out reactive checks or collect data to create proactive ones, accurate monitoring of attendance is necessary; in recent years, numerous monitoring methods have been proposed that allow the detection of occupants in the premises. The most popular are GPS detectors, Wi-Fi network connection detectors, PIRs (infrared motion sensors) and carbon dioxide concentration meters. Although from a conceptual point of view the methods are quite widespread in scientific literature, they have not found much application in public structures. The problem, as we have seen, has become relevant again in recent years. Following the spread of the COVID-19 virus, the need to ensure good air quality was imposed in public facilities and as a rule to reduce the spread of the virus.

This is a significant problem especially in buildings with a high occupancy rate such as schools and universities [13] and has brought the topic back. Ventilation therefore returns to play a fundamental role in mitigating viral loads in a confined space and its regulation to reduce energy consumption must not compromise the healthiness of the environments, two apparently opposing needs.

One method to pursue both objectives is to exploit the monitoring of carbon dioxide concentration; this parameter is directly correlated to the number of users present in the building and appears to be a good index of air quality, little influenced by the surrounding climatic conditions.

Even if the CO_2 concentration appears to be a good parameter, it turns out to be very reliable in the case of small volumes, while it is clear that in large structures, such as university teaching centers, it is unthinkable to base the regulation on physical models, not even predictive ones; In fact, there are too many variables and random events that could compromise the coincidence of the dynamics described by the model with the real use of the properties. The opening of a door that suddenly increases natural ventilation, the early conclusion of a lesson, an exam that lasts beyond expectations or the unreported failure of windows and doors are some examples that can suddenly change the trend of carbon dioxide (CO_2) concentration. The trend in CO_2 concentration can certainly be correlated to the presence of people inside the structures. However, the correlation is not always very strong because it also depends on the operational management of the spaces. For example, the Figure 5 shows the result obtained in 10 different CO_2 measurement sequences in the same classroom following the same class for a period of 4 hours.

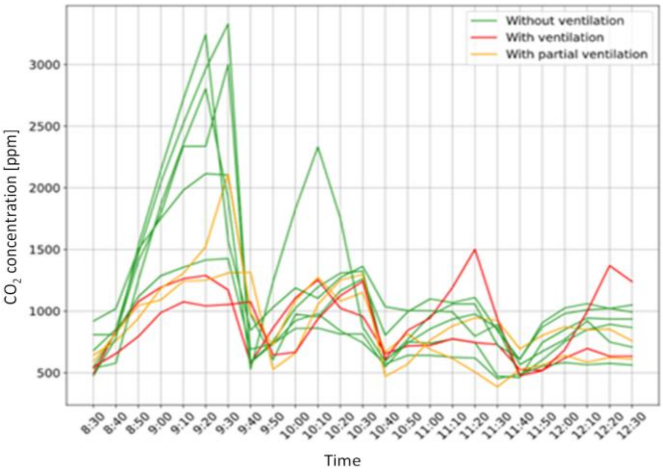

Figure 5. Measured CO_2 profiles in a specific room in similar conditions in ten different experiments

The data are discussed in detail in reference [14]. As it is possible to observe, there are some similarities, but it is not easy to understand what really happened inside the classroom. In fact, in some cases the windows were completely closed, in others some windows were open, while in other situations mechanical ventilation was active. Despite the various problems and all the uncertainties mentioned previously, CO_2 monitoring still appears quite well correlated with space occupancy. Since some environmental monitoring sensors are also equipped with movement sensors, it was therefore decided to evaluate the possible connection of the CO_2 monitoring data with the movement data detectable using the specific sensor. Figure 6 shows the sensor used to make this type of detection and the 9 different quantities that it can show. This is a commercial Smart D Home sensor, particularly the 9 in 1 sensor, which the authors of this work have also tested in several applications in various contexts in long-term trials [15].

Figure 6. Sensor 9 in 1 including CO_2 concentration and motion (PIR) sensor used in the experiments (https://www.smartdhome.com)

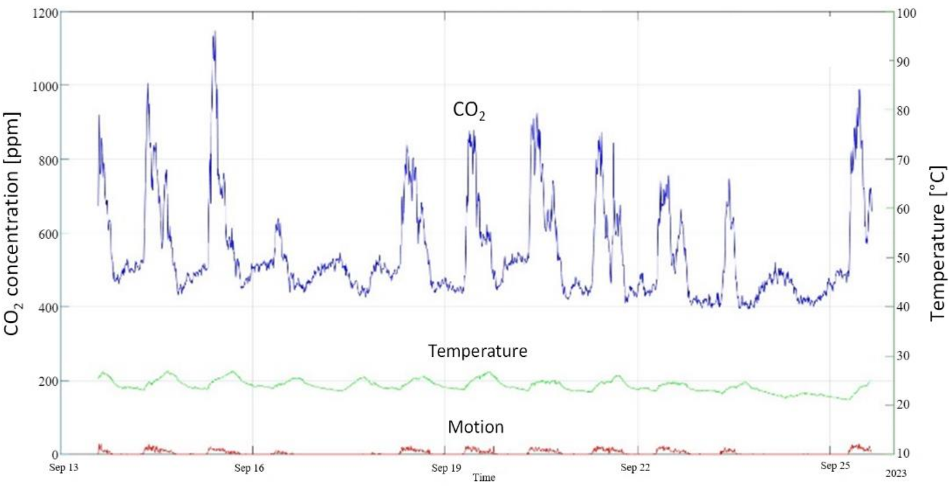

Figure 7. Correlation of CO_2 concentration (blue), temperature (green) and motion (red) in an experiment

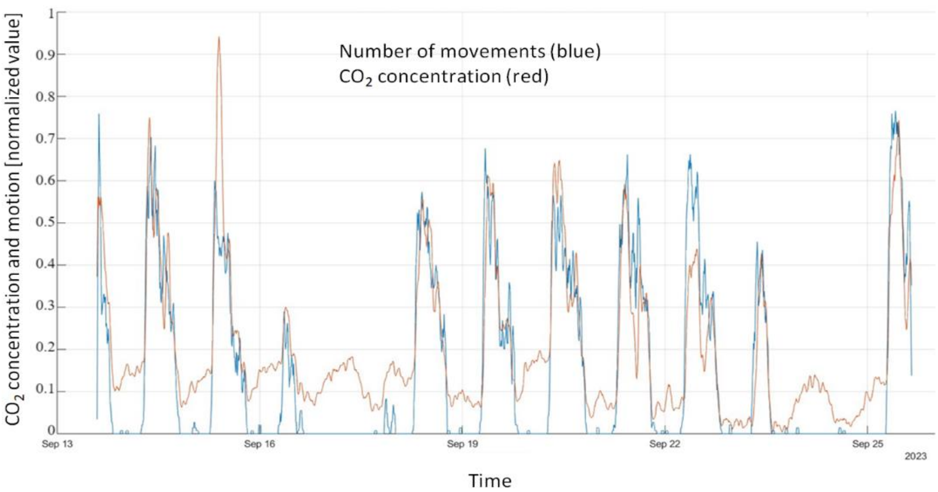

Figure 8. Correlation of CO_2 concentration and motion data

As can be seen from Figure 7, which reports the data of a long-term test (of 12 hours duration) carried out within a public health facility like university ones, there is a correlation between the CO_2 monitoring data and the movement data, even if the correlation seems to be quite weak (Figure 8). The motion sensor does not actually record the number of people as it is too sensitive to movements made in the vicinity of them, which are not necessarily correlated.

4. DEFINITION OF A MONITORING SYSTEM CONNECTED WITH IOT NETWORK

As should have emerged in the previous sections, there is considerable interest in pursuing objectives of optimized management of the energy use of very large and extensive structures. Table 3 shows, by way of example, some general data on the teaching structures that belong to traditional universities, such as the University of Pisa. The University of Pisa represents one of the 8 mega Italian universities, having a student population exceeding 45,000 enrolled [16]. These are housed in approximately 400 classrooms located in a significant number of teaching centers for a total of approximately 25,000 seats. Table 3 summarizes some dimensional elements. From the analysis of this table, we understand how the energy management of educational centers is quite complex for various reasons and how it is not easy to even think of a simple management based on local monitoring. There are in fact two problems. The first is linked to the very large number of sensors that would be necessary to control this type of structure and the second is the management of this data which would only make sense, if possible, remotely. In the following subsections we will show the method that was developed in the article we show how we tried to use the potential of low-cost sensors with those of a University IoT network, which can allow the different sensors to be connected. During the development of the activity referred to in the article, we arrived at the creation of an IoT architecture via MQTT based on sensors for monitoring various environmental parameters, connected to an Arduino ESP32 Nano microcontroller, which have demonstrated interesting potential for operation even if precision is not so high.

Table 3. Description of the University of Pisa

Characteristics	Data
Number of students	52000
Number of seats in the classrooms	25000
Number of dislocated didactic structures	30
Number of rooms for educational activities	440
Available surfaces	70000 m^2

4.1 Sensors

There are numerous sensors for measuring environmental parameters. The authors of this work tested three different types of sensors during the activity. They discussed the qualities of these sensors in a recent article, highlighting their strengths and weaknesses [15]. Those here proposed are low-cost sensors, which although not particularly precise from the point of view of measuring specific quantities, are nevertheless interesting for the envisaged architecture.

The multisensor architecture is composed, as can be seen from Figures 9 and 10, of two main elements:

•Grove environmental sensors, for sensing air quality parameters, including VOC (index), PM1.0, PM2.5, PM4.0, PM10.0, temperature, relative humidity, ambient noise, lighting and CO_2 and VOC (ppm);

•Arduino ESP32 Nano IoT microcontroller, for the acquisition and transmission of environmental data via MQTT protocol (Client/Publisher MQTT).

The various sensors are connected according to a modular logic to the respective microcontroller. The sensors do not have a user interface. For each parameter, the acquired measurement is directly transformed into an electrical signal to be sent to the control software; its value can be read on the management page.

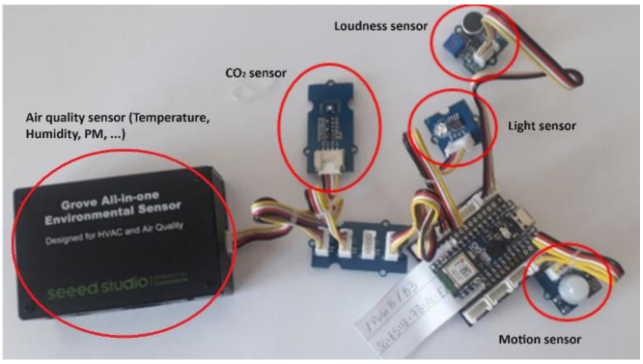

Figure 9. Complete architecture of the multi-sensor platforms equipped with all the components

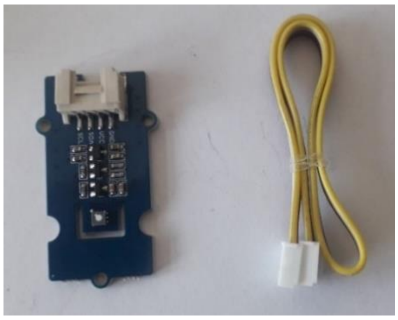

Figure 10. Zoom of the specific sensor for VOC and CO_2 concentration acquisition

4.2 The defined IoT network

To obtain significant results in the field of energy saving in complex structures, it is necessary that the building-plant system is entirely connected to the monitoring system and that the data can be controlled remotely. In this regard, it seemed useful to operate within IoT paradigm and use the potential of a dedicated network.

IoT is a technological paradigm conceived as a network of devices capable of interacting with each other. IoT is recognized as one of the most important areas of information technology development and is gaining an ever-increasing following across a wide range of application both in civil and industrial sector [17].

The architecture of the IoT network developed and referred in the paper is made up of 3 further essential elements, which are added to the architecture of the Arduino ESP32 Nano IoT sensors and microcontrollers, which can acquire environmental monitoring data and transmitting them through the transmission protocol MQTT (MQTT Client/Publisher). These 3 elements are:

1) the server (MQTT Broker), which is used for the

management and processing of the data collected by the monitoring system;

2) the Hidden Local Wi-Fi network for communication between devices (IoT network);

3) a personal computer or a different remote device that is used to connect the user with the central server to be able to view and perform data operations via VPN.

A software suite for receiving, processing, and storing MQTT messages and for data processing is mounted inside the Server. The suite is made up of:

•MQTT broker for receiving and routing MQTT messages.

•Node-RED for processing data taken from the Broker.

•InfluxDB for storing data in a local database and for real-time data visualization.

The complete system architecture is schematized in Figure 11.

The system considered is modular to be able to respond to the most diverse needs and consists of distributed monitoring using sensors wireless and the integration of the monitoring network with a latest platform generation for intelligent, automatic, or semi-automatic monitoring/control of existing systems, even remotely. The architecture, in addition to being relatively simple from a management point of view, is quite safe from an IT security point of view. This is because it is an internal network of the structure, which is not accessible from the outside, but only to authorized users in possession of the credentials to access the server.

Obviously, the system thus conceived has the undoubted advantage of the reduced cost of the sensors created, obtained by assembling low-cost sensors, and of being able to manage data coming from the many University structures in real time. The system we have designed, although not the primary focus of this article, also meets key requirements from a cybersecurity standpoint.

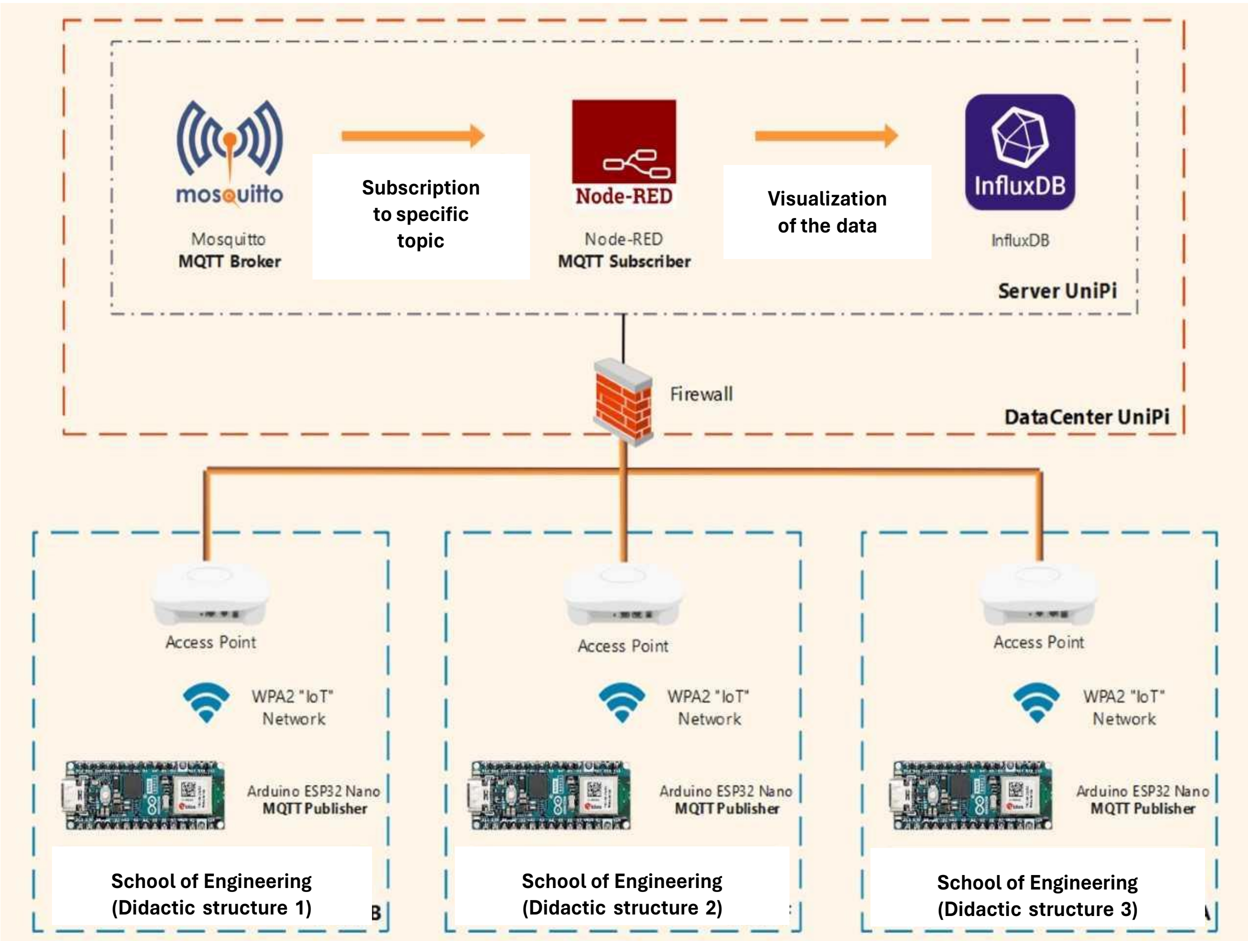

Figure 11. Architecture of the IoT network connecting three didactic structures of University of Pisa

5. PRACTICAL IMPLICATIONS AND APPLICATIONS TO A CASE STUDY

The availability of "occupancy data", obtainable from specific movement sensors and CO_2 monitoring sensors, of public structures is very useful for making energy optimisations. In fact, the systems are designed with respect to the project conditions (which generally correspond to high demanding conditions), and an operational optimization is not easy. The sensors that have been developed are relatively low cost and can provide a lot of data and information. As discussed in section 3, sensors have been created that can acquire 10 different types of data (among these, in addition to temperature and relative humidity data, also CO_2 concentration data, lighting data, movement data). These can be read from any remote access using the IoT network and can allow remote control of the systems. This can be very useful for example in the case of HVAC systems were monitoring their actual presence and regulating their operation can allow considerable energy savings, both for heating (cooling) and for mechanical ventilation. In fact, it could be very useful to be able to turn off the systems if the rooms are empty or turn them on as needed in the event of presence. One of the most relevant problems for educational structures is in fact that of highly variable employment: moments in which there is a very high occupancy alternate with moments in which is very low. Considering a closed environment, the following equation instead defines the mass balance for calculating the CO_2 concentration in a closed environment; it is a function of the production of carbon dioxide per capita, but also of the ventilation rate, whether introduced mechanically or naturally, or by infiltration through windows and doors. From a conceptual point of view, an effective control system for the operation of the HVAC system, in the case of a small environment, could be based on a control of the concentration of CO_2 or on that of its derivative, based on the model defined by Eqs. (8) and (9), in which the CO_2 concentration rate is a function of the volume of the space (V), of the rate of CO_2 production ($\dot{r}$), on the number of occupants and on the ventilation rate, $\dot{m}$ (natural or mechanical or both).

$$C_{\{CO_2\}}(t) = C_{\{CO_2\}}(t=0) \cdot e^{\left(-\frac{\dot{m}}{V}t\right)} + \left(C_{\{CO_2\}_{ext}} + \frac{n_{occ}}{\dot{m}} \cdot \dot{r}\right) \cdot (1-e)^{\left(-\frac{\dot{m}}{V}t\right)} \quad (8)$$

$$\frac{dC_{\{CO_2\}}}{dt} = \frac{n_{occ}}{V}\dot{r} - \frac{\dot{m}}{V}\left(C_{\{CO_2\}}(t) - C_{\{CO_2\}_{ext}}\right) \quad (9)$$

Based on the detected value of the concentration of CO_2 within the environment and the difficulty in considering it closed, a feedback system could still be implemented on the fan which allows it to vary its frequency and therefore its flow rate or even deactivate it (with a type of regulation on-off).

Just to show the interesting potential of the method we tried to apply it to one of the three didactic structures of the School of Engineering of the University of Pisa, tested (Figure 12).

The problem that often arises, however, is that the HVAC systems of the educational centres are quite complex and serve different areas of the same building, so that it is not so simple control and regulation of the system [18]. For this reason, the developed sensors and methodology could be very useful, increasing the number of measurement points and trying to define optimal logic for the control of HVAC devices [19].

To evaluate the savings potential, a particular structure has been analysed, simulating the operation of the HVAC system based on a control logic imposed by monitoring data.

The first logic is a modulation of the flow rate based on the request. The second is the classical ON-OFF logic, which involves turning on the fan only when CO_2 concentration reaches a threshold value set at 1000 ppm [20].

Figure 12. Aerial view of one of the three didactic structure tested (surface: 2134 m^2, volume: 10296 m^3 and maximum occupancy: 1590 students)

Table 4 reports the values obtained in three different weeks of Winter period. The results show how ON-OFF regulation mode with the system's switch-on threshold at a carbon dioxide concentration of 1000 ppm proves to be the most efficient management method from an energy point of view in all cases analyzed. Only in case of reduced occupancy (Week 2) are electricity consumption lower when the system is controlled by logic that follows modulation rather than intermittent operation.

Table 4. Energy saving with HVAC control based on CO_2 concentration in the structure of Figure 12

	Energy Saving	Modular Regulation		ON-OFF Regulation	
	Air volume saved [m^3]	457900	20.8%	905600	41.1%
Week 1	Thermal energy saved compared to design [kWh]	240.9	41.1%	325.7	55.5%
	Electricity saved compared to design [kWh]	698.2	34.5%	836.6	41.3%
	Air volume saved [m^3]	1166670	53.0%	1739300	79.0%
Week 2	Thermal energy saved compared to design [kWh]	2765.9	66.2%	3137.4	75.1%
	Electricity saved compared to design [kWh]	1811.6	89.5%	1600.3	79.0%
	Air volume saved [m^3]	457900	20.8%	905600	41.1%
Week 3	Thermal energy saved compared to design [kWh]	1268.7	25.6%	1880.5	38.0%
	Electricity saved compared to design [kWh]	704.8	34.8%	850.4	42.0%

In Table 4, three sample weeks during the heating season (winter), each characterized by different climatic conditions and occupancy levels, are analyzed to highlight how careful monitoring of student presence and direct feedback on system operation could lead to significant energy savings.

These savings would be achieved both considering the air flow rate based on conventional system operation, where air volume is exchanged at full load (considering that regulations require a 6 Vol/h air exchange), and in terms of energy used for ventilation and heating.

The three weeks examined are:

Week 1: late March, featuring mild winter conditions and high occupancy during the teaching period.

Week 2: mid-February, with moderate winter conditions and low occupancy during the exam period.

Week 3: late November, marked by harsh winter conditions and high occupancy during the teaching period.

The advantages could be even more relevant in summer mainly during the weeks in which high temperature and reduced occupation of the rooms is observed.

6. CONCLUSIONS

The objective of this article was to evaluate the potential benefits that an IoT-interconnected system can bring to the energy management of shared public buildings, particularly university teaching centers. Specifically, the development of an IoT network for monitoring environmental parameters, such as occupancy levels, was highlighted, demonstrating its capacity to inform energy-saving policies. This real-time data integration allows for more dynamic and efficient control of building systems.

The case study demonstrated significant potential for energy savings, with reductions ranging from 25-30% in weeks with mild weather conditions to up to 80% in periods of low occupancy and favorable climate. These findings suggest that optimized control of building systems, based on real-time data, can lead to substantial improvements in energy efficiency. Although these results are most pronounced in milder seasons, they remain meaningful during colder periods when ventilation systems are heavily used.

Overall, this study illustrates how IoT networks can be key in achieving energy efficiency in public structures, providing not only cost savings but also enhancing user comfort. Future work may explore further applications of IoT in building management and address challenges such as scalability, cost, cybersecurity and data privacy.

ACKNOWLEDGMENT

This paper was supported by Regione Toscana in the framework of the Research Project RE-START (Grant No.: I55F21002530002).

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NOMENCLATURE

C	concentration rate, ppm
c_p	specific heat, J kg^{-1} K^{-1}
h	specific enthalpy, J kg^{-1}
$\dot{m}$	mass flow rate, kg s^{-1}

n_{occ}	number of occupants
p	pressure, Pa
P	power, W
$\dot{r}$	CO_2 metabolic production rate, ppm s^{-1}
t	time, s
T	temperature, °C
V	volume, m^3
Dp	pressure losses, bar
r	density, kg m^{-3}

Subscripts

CO_2	of carbon dioxide
con	concentrated
dehum	dehumidification
dis	distributed
ext	external conditions
hum	humidification
id	ideal value
loc	local
pre	before treatment section
post	after treatment section
set-point	set-point value
th	thermal
tot	total