Sustainable Cities and Society 82 (2022) 103876

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Iterative Optimization of a Social Inmotics-Based Method in Order to Make Buildings Smart and Resilient

Beatriz Montalbán Pozas [a,*], Beatriz Muriel Holgado [a], Marta Lucas Bonilla [a], Sergio Barroso Ramírez [b], Pablo Bustos García de Castro [b]

[a] *Departamento de Construcción, Escuela Politécnica de Cáceres, Universidad de Extremadura, Av. de la Universidad s/n 10003, Cáceres, Spain, 0034 927 25 71 95 - 0034 649 271 463*

[b] *Departamento de los Computadores y de las Comunicaciones, Escuela Politécnica de Cáceres, Universidad de Extremadura, Av. de la Universidad s/n 10003, Cáceres, Spain*

ARTICLE INFO

Keywords:
smart and resilient buildings
building energy consumption
Indoor Environmental Quality
monitoring
social inmotics
key performance indicators

ABSTRACT

The current situation of inefficiency in buildings operation, inadequate occupants' habits and the low Indoor Environmental Quality suggests a methodology that addresses the implementation of social inmotics. The method allows the continuous optimization of the building performance and occupants' awareness through an iterative process. In each iteration the experts propose strategies that will be evaluated in the next cycle through key performance indicators. This method develops an open source, scalable, low-cost cyber-physical system using real time data. The results have been obtained from successive approaches, implementation of protocols and empirical validation in different scenarios until reaching the version of the system installed in a public university building, the School of Technology (University of Extremadura, Spain). By testing this methodology, social inmotics through the use of disruptive technologies is proving to find solutions that increase energy savings and improve Indoor Environmental Quality in adaptive and resilient buildings. Some of the results show that electricity and water consumption with respect to occupancy density have decreased, important and unexpected consumption peaks as the data servers, the cafeteria, or breakdowns have been detected, and users' participation improve the initial situation. Furthermore, this paper provides key performance indicators for this building typology.

Specific abbreviations used

CPS	cyber-physical systems
EPCC	School of Technology of Cáceres (Escuela Politécnica de Cáceres)
EU	European Union
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
iBEMS	intelligent Building Energy Management System
IEQ	Indoor Environmental Quality
IS	Information System

1. Introduction

Buildings and the construction sector together account for over one-third of global final energy consumption and about 40% of total CO_2 emissions (International Energy Agency, 2020). Thereby, some of the priority issues defined in the Urban Agenda for the EU, as part of the latest Pact of Amsterdam in 2016, are energy transition, adaptation to climate change, air quality and housing (European Commission, 2016). Thus, a long-term strategy has been established to contribute to the renovation of buildings into highly energy efficient and decarbonized ones by 2050, by facilitating their cost-effective transformation into nearly zero-energy buildings and by reducing greenhouse gas emissions by 80-95% compared to 1990 levels (European Commission, 2020). However, energy consumption in the EU due to buildings remains stable and accounts for 40.3% of total energy use (of which residential is 26.1% and the service sector is 14.2%) (Eurostat, 2020). One of the reasons for the increase in energy use is that most of the population nowadays spends 90 % of their time indoors, using mechanical HVAC equipment to

* Corresponding Author.
E-mail addresses: bmpozas@unex.es (B. Montalbán Pozas), beatrizmh@unex.es (B. Muriel Holgado), malucasb@unex.es (M. Lucas Bonilla), sbarmirez@unex.es (S. Barroso Ramírez), pbustos@unex.es (P. Bustos García de Castro).

https://doi.org/10.1016/j.scs.2022.103876
Received 26 January 2022; Received in revised form 29 March 2022; Accepted 30 March 2022
Available online 6 April 2022

maintain comfort conditions (Cao, Dai, & Liu, 2016). In this use of the Earth's resources in buildings, the uncontrolled use of water must also be added (The European Parliament and the Council of the European Union, 2000).

Currently, energy efficiency parameters are applied in the design phase of buildings in some cases. Nevertheless, no follow-up study is carried out during the building's operation phase to verify that the actual conditions correspond to the calculated parameters; therefore, there is a lack of information on the buildings behavior and their construction elements (Allab, Pellegrino, Guo, Nefzaoui, & Kindinis, 2017). The occupants' habits are also of great impact on the energy performance of buildings and can lead to considerable improvements (Pan et al., 2017; Stazi, Naspi, & D'Orazio, 2017). Hence, after simulating occupant behavior in different types of buildings, it has been proven that occupant behavior affects energy savings by up to 20% in buildings where high occupant interaction is required to achieve these savings (Sun & Hong, 2017). Likewise, the unknown variables of operation and energy consumption by occupants aggravate the situation (Almeida, Tam, & Le, 2021). In addition, the need to analyze building performance in terms of IEQ to guarantee occupants' thermal comfort with the lowest possible energy consumption is raised (Kim, Hong, Kong, & Jeong, 2020).

Moreover, obsolescence and improvement of buildings operation is seen as a problem by many policymakers, which must be addressed urgently (Buitelaar, Moroni, & De Franco, 2021).In this sense, there are currently a wide range of possibilities and technologies for monitoring to ensure the improvement of building performance and indoor environment (Ahmad, Mourshed, Mundow, Sisinni, & Rezgui, 2016): by tracking the human-building interaction, collecting surveys and data logger measurements of the thermal behavior (Hong, Yan, D'Oca, & Chen, 2017; Langevin, Gurian, & Wen, 2015), or by identifying and optimizing energy consumption (Melzi, Same, Zayani, & Oukhellou, 2017), as well as by managing thermal comfort using smart thermostats and surveys (Stopps & Touchie, 2020); and by integrating energy and occupant satisfaction at the operational stage (Wang & Zheng, 2020), or by occupant-centric building control (Park et al., 2019).

Other parameters to be considered with respect to IEQ may be IAQ, lighting or noise (Technical committee AEN/CTN 100, 2007). Besides, experiences in monitoring carried out in laboratories, experimental buildings, previously designed modular units, or even complete neighborhoods have also been collected (Instituto de Ciencias de la Construcción y Consejo Superior de Investigaciones Científicas, n.d.). Taking all of the above into account, the EU is implementing strategies that should be submitted to promote smart technologies and well-connected buildings and communities (The European Parliament and the Council of the European Union, 2018).

Furthermore, it is relevant to develop CPS where physical systems act as sensors to collect real-time information and communicate with the computation modules in order to improve building operational performance (Alam & El Saddik, 2017; Bonci et al., 2019). At the present, the minimum data required for the improvement of building performance have been defined (Xiao & Fan, 2014). For this, it is essential to adequately design both the sensors, which must transmit data in real time (Vellei, Natarajan, Biri, Padget, & Walker, 2016) for proper decision making in relation to their management and maintenance (Burgas, Melendez, Colomer, Massana, & Pous, 2015), as well as the monitoring system that involves occupants in issues, such as the resources used and improvements in IEQ (Sharmin et al., 2014).

To complete the system, a control procedure, iBEMS, is needed in order to integrate the different monitored parameters of the building (Papantoniou, Mangili, & Mangialenti, 2017). These iBEMSs must be able to find the balance over minimizing energy cost and maintaining users comfort (Aslam et al., 2017; Khalid et al., 2020). In addition, the use of open communication protocols allows for independence from proprietary systems, better scalability and reproducibility, as well as low cost (Ciuffoletti, 2018; Priyanka Jain, 2018). The Enterprise Service Bus facilitates communication between software agents, while integrating and managing multiple information sources with different access methods. The implementation of Digital Twins in CPS constitutes a breakthrough in this field (Chaudhari, Bhadoria, & Prasad, 2017).

Presently, there are great technological advances regarding *digitization*, whose application, however, has not been extended to the urban environment, where it is used in a very isolated way both in new cities or buildings, and in renovation and/or regeneration actions, through the concepts of smart city/village/building (Park et al., 2019). The concept of Smart Cities and Communities and their benefits for society will become a reality in the coming years, the technologies included in the term SmartX, such as Cloud Computing, Big Data, Artificial Intelligence or the Internet of Things are evolving significantly while being integrated into different sectors of society (Fortes et al., 2019).

There are experiences through which smart strategies have been implemented in different building uses: offices (Bamodu, Xia, & Tang, 2017), residential (Stopps & Touchie, 2020), public residential (Burgas et al., 2015), non-residential (D'Agostino, Cuniberti, & Bertoldi, 2017), and educational (Fernández-Caramés & Fraga-Lamas, 2019). In this context, Smart Campuses appear as ideal spaces to develop research in this field (Álvarez, Raposo, Miranda, Bello, & Barbero, 2019; Martins, Lopes, da Cruz, & Curado, 2021), in which different objectives are proposed: from the optimization of the spaces occupancy, to the efficiency and comfort improvement, or the facilities security control (Gilman et al., 2020), and mainly to expand knowledge and education in the construction and energy efficiency sectors (The European Parliament and the Council of the European Union, 2018). The observed evidence in many facilities shows a wasteful use of energy resources and water, thermal discomfort and/or inefficient use of spaces and resources (Sanchez & Oliveira, 2018). For this reason, systems that allow resources' control and maintenance are implemented, so that the buildings that integrate a smart campus are gradually more efficient and adapted to the actual occupants' demand (Alghamdi & Shetty, 2016). Consequently, some experiences emerge: in France (Allab et al., 2017), in Australia (Khoshbakht, Gou, & Dupre, 2018), or in Spain: in the Campus of Cáceres (Montalbán Pozas et al., 2018) and Málaga (Fortes et al., 2019). Furthermore, the evaluation or any actions should be considered essential. Thus, key performance indicators that measure the effectiveness in achieving goals in smart buildings are employed (Joud Al Dakheel, Claudio Del Pero, Niccol`oAste, 2020; Technical committee AEN/CTN 100, 2007), to ensure the proper building operation and for monitoring the control system (American Society of Heating and Air-Conditioning Engineers (ASHRAE), 2020; Federation of European Heating & Air Conditioning Associations (REHVA), 2019).

Given this background, this article proposes a methodology through an iBEMS with an open, scalable, replicable and low-cost CPS, which, in an automated way, manages the monitoring, control and performance of the building's operation and its occupants' behavior, with the inclusion of continuous evaluation indicators. The system, of technological development, progressively transforms conventional buildings into smart ones, by a social inmotic system, which allows incrementally improving the buildings behavior, by reducing the use of resources and improving the IEQ, as well as any other parameter that may be introduced in the future. The system authorizes real-time data visualization and the implementation of improvement strategies to enable user interaction, along with governance by managers and administrators for proper decision-making. The applied research in the field of smart campus has been extended to the case study of a public university building in a Campus, EPCC, and can be implemented both in other existing buildings as well as in new buildings, filling the information gap that exists in the operation and maintenance phase.

2. Methodology

The methodology proposed in this article is organized in a circular iterative scheme optimizing the efficiency of the building incrementally in each cycle. The final objective is to validate a series of strategies. These are proposed by experts and then evaluated through indicators in every iteration. These indicators are calculated periodically, and they will show the effectiveness of the method. The proposal presented in this article has been developed through successive approximations of the method and the practical validation of its different phases in several scenarios. Variants of the different phases of the methodology have been put into operation in each scenario (Montalbán Pozas, Amigo Gamero, Domínguez Sánchez, & Bustos García De Castro, 2020; Núñez et al., 2020).

Thus, the system is developed in four phases. In the first phase, the characterization is carried out with static data relating to the physical model of the building and its occupants. Thanks to this work, a prior evaluation aiming to identify the possible problems that the building may present is obtained. The second phase is based on the previously generated evaluation report. The IS is designed to manage the data which, in turn, must be captured by the sensor network and then monitored obtaining dynamic data. In the third phase, static and dynamic data are incorporated into the analysis. Thanks to this information, the experts propose improvement strategies and define indicators. Finally, a control and actuation system completing the IS is established in the fourth phase. On the one hand, this system programs campaigns or messages, warnings, alarms and actuators. On the other hand, it programs new indicators designed to compare with each other when the system begins to iterate, correcting the previously designed strategies. In addition, the process improves the design throughout phases: the IS of phase 3 corrects the model of phase 1, and the phase 3 indicators refine the IS of phase 2 (Fig. 1).

2.1. Model characterization

At first, the physical model and its occupants are characterized through static data. There are several classifications proposed in the literature that stand out some influential factors, discerning between external and internal influences (Ministerio de Fomento Gobierno de España, 2017). On this basis, the classification used in this project distinguishes among six factors:

- Location and climate: define the unique geographic and climatic conditions, such as latitude, orography, landscape unit, height above sea level, geographic orientation or shadows affecting the building. It also takes into account other factors as temperature, relative humidity, solar radiation or pluviometry.
- Thermal envelope: characterizes the building from a typological and constructive point of view. For that purpose, it uses data on volume, floor area, year of construction, building elements, characteristics of walls and openings, air infiltration and thermal bridges.
- Systems and supplies: record the energy supply systems used, either for HVAC, lighting or equipment supply, or water supply. It also collects other internal or external services, such as communication and information networks and infrastructures.
- Interior design: defines the configuration of the space through the number of floors, rooms, usable area and heights, among others. Moreover, it differentiates between living/non-living, outdoor/indoor or heated/unheated areas.
- Occupancy: provides information on the number of users, distribution and schedules of the habited spaces,
- as well as the occupancy density by zones.
- Operation and maintenance: monitor the use and the maintenance of the building, and track the references to detected incidents and pathologies, reforms and post-construction works, or, if it existes, an action plan.

At this moment, a preliminary evaluation of the building may be carried out after its characterization. The goal is to identify its requirements, which will be established for the subsequent design of the IS.

2.2. IS design

The architecture of the system must be able to host, maintain, relate and offer all the acquired data. It is described by its main elements depending on where the programs are executed: the management system (back-end) and the visualization system (front-end), both interrelated through the service bus. Along with the time series generated by

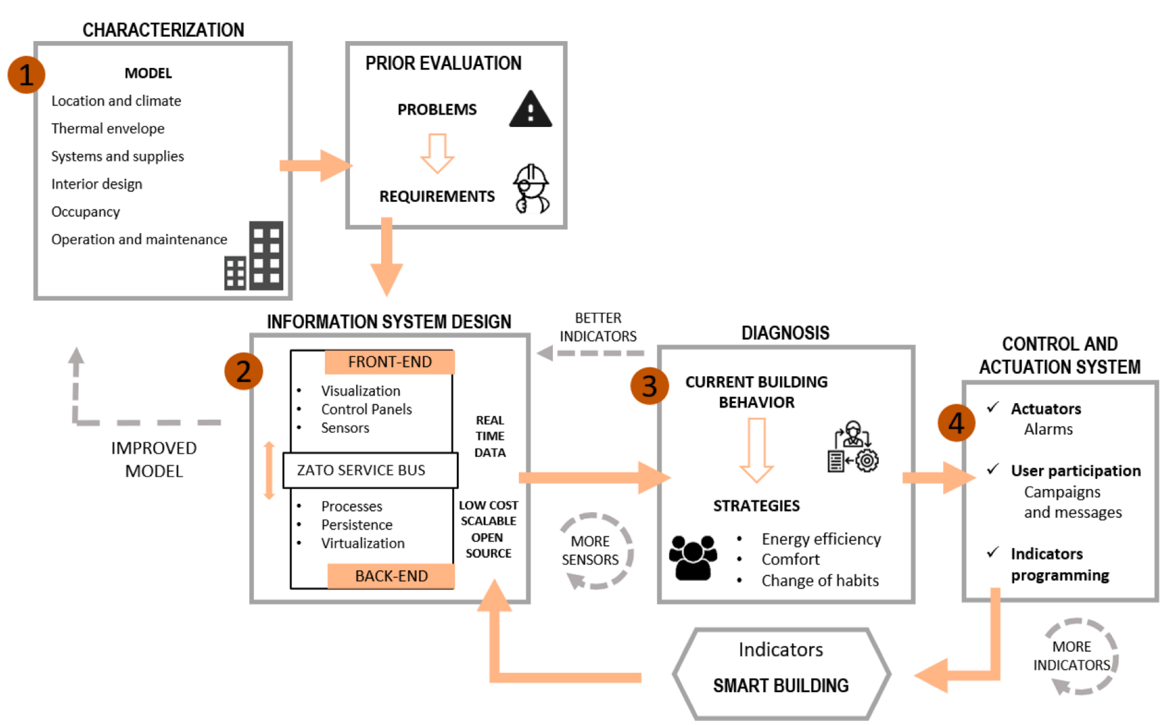


Fig. 1. Flow chart of the methodology.

the sensors, the IS must maintain static and dynamic data of the building. Data must be organized in such a way that they represent with sufficient fidelity the physical entity of origin. The organization of this mixed information is essential to facilitate its access, visualization and the creation of more complex predictive models.

This methodology suggests using two databases: one oriented to graphs, with the objective of representing the spatial structure of the building, and another one of time series, with the aim of storing dynamic data. Both databases must be interconnected through the code that is integrated into the IS. It is also highly advisable that they be open source to guarantee the quality and security of the code.

A generic and easy proposal to deploy in this phase is to start from one or several virtual machines that can be on their own infrastructure or in the cloud. Databases are installed on one of the virtual machines. The other machine will host a software known as a service bus that exposes all the IS services outside. The service bus is also responsible for connecting internally and securely with the databases and other programs in charge of the internal logic of operation. The IS must therefore have the following parts:

- Back-end: receives and stores the information, and provides access. That way, this information can be consulted. It is made up of 3 layers: the virtualization infrastructure (virtual machines and servers), persistence (open-source database storage systems) and logical processes (programs that allow data to enter and exit the system; they check these data and implement security measures to safeguard the integrity of the system).
- Service bus: programs that monitor, manage and supervise the execution of services. They also offer various functionalities related to communication protocols and how services are offered.
- Front-end: contains the views section, which includes the data collection sources, like sensors. They can generate a series of data related to different variables. An IS such as the one detailed here requires the collection of data from the physical world. Therefore, the ultimate goal is to install a large number of sensing devices progressively. These tools must have the capacity to measure data from the environment and the state of a set of variables of interest. Open connectivity devices should be chosen to facilitate connection to the IS and their subsequent expansion.

In addition, and despite the variety of devices, all of them must have integrated communication capabilities with servers. For this purpose, they must use well-established protocols that are implemented in the service bus. The most common practice is to use a REST API over HTTP. The means of connection to the IS must be taken into account. For this reason, a feasibility study of network connections, and of the necessary maintenance is required. The data transfer options are the following: publication from the devices to the server, using standard protocols such as REST or MQTT, and periodic query either to the device or to an intermediate storage location from the server. The latter case occurs when, for example, the LoRaWAN network is used. In this case, packets are retrieved from their servers. This requirement for open operation makes it unfeasible to use many of the existing low-cost sensors (they do not allow re-configuration and only send data to proprietary systems). The visualization system uses tools to allow users to access the data presented in different ways. It is vital that these tools are also open to allow them to be connected and, if necessary, be replaced.

2.3. Diagnosis and strategies definition

In this part of the methodology, the dynamic data obtained through the IS are analyzed, added to those coming from the static characterization of the building. Finally, the diagnosis is made. In this way, the state of the building is fully defined, and it is then possible to propose strategies, which may be aimed at reducing energy demand directly (in systems or equipment) or indirectly (envelope, use and distribution, actions such as ventilation, shading, etc.), improving comfort, informing, or raising awareness and modifying the behavior of users. These strategies must be validated by defining indicators that reflect the improvements produced in the system in each iteration. They must also characterize the behavior of the building and allow verification of compliance with the objectives pursued.

2.4. Design of the actuation and control system

Next, the protocols and rules of action and control are established, which must be set in order to put into practice the strategies established in the previous phase. Their implementation can be carried out through the programming of alerts or warnings, campaigns and messages of persuasion, information and participation, or automated processes for optimizing the system through the monitoring of previously defined indicators and some that will be defined in this stage of the methodology.

3. Results and discussion

The specific results of the EPCC building case study are presented. These results are obtained from the proposed methodology.

3.1. EPCC model characterization

The parameters mentioned in section 2.1. are developed below:

3.1.1. EPCC location and climate

The EPCC is located on the campus on the outskirts of the city of Cáceres. The area is flat and low, precisely 367 m above sea level (about 100 m below the level of the city center). The campus has a very low density of occupation, little vegetation or green areas, and no nearby bodies of water. The building is not affected by external shading, and the immediate surroundings are paved or asphalted.

The climate is Mediterranean with climate zone Csa, according to Köppen-Geiger. According to the Spanish Technical Code, it is C4 with medium climatic severity in winter and high in summer. There is a climatic station very close to the EPCC. It collects data of high solar radiation, minimum average temperatures in January of 3.7 °C, and a maximum of 33.7 °C.

3.1.2. EPCC thermal envelope

Most of the buildings that make up the EPCC were built in 1989. There are four long-isolated pavilions with predominant facades, three of them East-West and one North-South. Years later, in 1999 and 2009, the EPCC was extended with two more isolated buildings. Thus, the total built area is about 23,000 m^2, distributed over two or three floors (Fig. 2). The envelope of the oldest buildings is made up of walls of 1 foot of brick, 5 cm insulation and a 7 cm brick interior partition wall. The roof is flat and non-trafficable with 5 cm insulation. The openings are made up of aluminum carpentry without thermal bridge break, with double glazing and a chamber, and obsolete shutter boxes with high thermal bridges. These buildings also have large roof skylights made of thin polycarbonate without shading.

Thermographic, thermal transmittance and air tightness tests were carried out to complete the characterization of the envelope. Thanks to these tests, thermal bridges and infiltrations were identified. In addition, the existence and effectiveness of thermal insulation, both in walls and in the roof, was confirmed.

3.1.3. EPCC systems and supplies

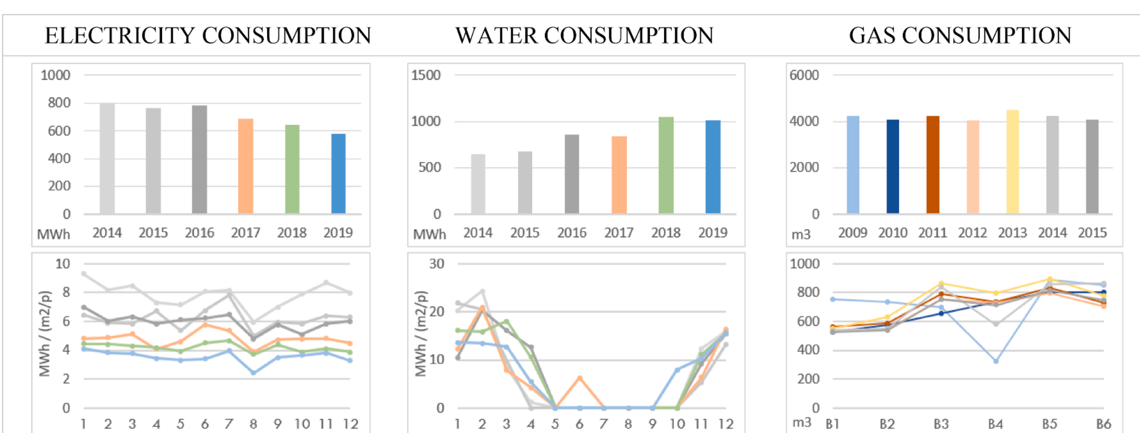
The EPCC is supplied with electricity for lighting, equipment power supply (mainly servers and computer equipment), HVAC (mainly with natural gas for heating), and drinking water supply for consumption in bathrooms, laboratories and cafeteria, as well as for cleaning the center. In addition, photovoltaic panels with a power of 10 kW are installed. The

Fig. 2. Exterior and interior views of EPCC: panoramic view, ground floor hall, classroom, meeting room, first floor hall and laboratory (from left to right and from top to bottom).

EPCC also has two internal data networks: a Wi-Fi network, and an internal and wired network with limited connection points. In addition, a LoRa antenna is available.

As the center's overall monthly bills for the last six years are usable, the historical and habitual consumption is known. It should be pointed out that the data for the years 2020 and 2021 have been discarded for being unusual. The regular operation of the building was modified because of the worldwide SARS-CoV-2 pandemic. Regarding water consumption, there has been no meter since 2015, so the seven years prior to 2015 have been selected. Moreover, the billing is calculated by a participation coefficient of the entire campus, so it is not accurate. It is considered that the most representative indicators to evaluate each consumption should not only be the global ones. It has been possible to calculate the temporary average consumption indicators per person, surface area, volume, or/and occupancy density. The most relevant ones are: in electricity according to the occupancy density (kWh/(m^2/p)); in natural gas, according to the heated volume (kWh/m^3); and in water, according to the users (l/p) (Fig. 3). From the data analysis, it can be seen that:

- The overall annual electricity consumption has generally decreased progressively since the first year. This drop is in line with the decrease in the number of students. The annual average for the period was 711 MWh.
- The lowest monthly values occur when facilities are closed (the minimum registered was 2.4 MWh/(m^2/p) in August 2019). In contrast, the highest monthly values happen in the cold months (the maximum was 9.3 MWh/(m^2/p) in January 2014). In non-school winter periods, high consumption is observed. This is probably due to the use of individual electric heaters. In addition, a high base is generally observed even in the closed season (the minimum was 33 MWh in August 2019). Consumption per occupancy density, like total consumption, has been progressively decreasing (from 7.8 to 3.5 MWh/(m^2/p)). The monthly average in the analyzed period was 5.4 MWh/(m^2/p).
- On the other hand, the analysis of water consumption does not show a clear trend in its annual or bimonthly behavior, apart from a reduction in non-school periods. The annual average for the period is 4,213 m^3. In contrast, the monthly average per person for the period analyzed is 4.7 liters per day.
- Natural gas consumption shows an annual upward trend, except in the last year, when it decreased slightly. The annual average for the period is 848 MWh, with high dispersion. The maximum monthly record was 3.73 kWh/m^3 in February 2017. Higher consumption is observed in January and February. On the contrary, it is null from



	Mean/ standard deviation		Mean/ standard deviation		Mean/ standard deviation
Yearly	711 / 87 MWh	Yearly	4213 / 158 m³	Yearly	848 / 166 MWh
Monthly	3,0 / 0,4 kWh/m² 31,1 / 3,0 kWh/p 5,4 / 1,6 MWh/(m²/p)	Monthly	142 / 21,5 l/p	Monthly	2,1 / 0,4 kWh/m³ 77,6 / 22,1 kWh/p 12,7 /1,4 MWh/(m²/p)
		Daily	4,7 / 0,7 l/p		

Only the months when the heating system is on have been taken into account for gas indicators.

Fig. 3. Graphs of annual and monthly evolution of total consumption of the EPCC (data from invoices) and data indicators and statistical metrics.

May to October (both included). The monthly average for the analyzed period is 2.1 kWh/m^3 again, with a high dispersion of results.

3.1.4. EPCC interior design

The usable space is mainly made up of classrooms, laboratories, offices, restrooms and large common areas spread over 21,000 square meters. Five of the buildings have large double-height spaces with longitudinal interior patios linking several floors. The interior carpentry is mostly made of wood, although metalwork can also be found. The interior walls are plastered or tiled. In addition, there are modular or continuous false ceilings in some spaces, especially on the upper floor, and the floor is made of terrazzo (Fig. 2).

3.1.5. EPCC occupancy

Students, teaching, research and administration and services personnel use the building. The theoretical occupancy has been calculated according to the number of enrolled and hired personnel. The number of users has been decreasing in the last five years, from about 2,300 to about 1,400 at present. In addition, several surveys have been carried out to diagnose the profile of the main user, and to know the personal involvement and the feeling of comfort in the building. The average profile corresponds to a man between 22 and 24 years old studying in the last courses, who lives in the city in a shared apartment with other classmates, and drives to the university in his own vehicle. Fig. 4, 5, 6, 7, 8, 9, 10 and 11.

3.1.6. EPCC operation and maintenance

The school serves as a teaching and research center. It is open from Monday to Friday, from 8 a.m. to 10 p.m. Spaces are occupied in a wide variety of ways depending on teaching schedules. Some of the buildings are sometimes used on weekends for public examinations or events. The buildings have not been renovated since their initial construction due to a lack of budget. For this reason, only corrective maintenance has been carried out to solve the most critical flaws. It is worth mentioning the installation of hot air extraction chimneys in three of the pavilions in mid-May 2019. However, as they are not sensorized, the extracted air flow rate is unknown.

3.1.7. EPCC prior evaluation

After the previous characterization of the building, it is possible to infer the different problems presented by the building in each of the characterized parameters. This analysis will be used to design the IS requirements:

- severe climatic zone in summer, with high direct and indirect solar irradiation
- façades with unfavorable solar orientation, high thermal losses and gains due to infiltrations, and absence of solar protection - no pre-installation of infrastructure for data networks to connect smart devices
- lack of sectorized real time information on energy consumption; high electricity consumption base, even during the closing season; many connected devices without consumption and schedule control; missing protocols of natural gas consumption for heating; no control of faults in the water network
- air stratification due to double heights
- very long hours of use, with high mobility and variability in the number of occupants; incorrect habits of use
- obsolete construction and lack of preventive or predictive maintenance

Following these issues, the requirements for the design of the IS are established. The sensor network must be low-cost, and both the electrical and the data network must be wireless. In addition, it must provide real-time data to allow immediate corrections on a smaller and sectorized time scale. Depending on the type of sensors, a different requirement is set as follows. Hygrothermal sensors should help establish strategies for solar gain/protection and ventilation according to the specific space, and the automated control of HVAC systems; in this regard, it is recommended to sectorize the systems for better adaptation to the occupancy. Electrical network analyzers will allow locating excessive electrical consumption and devices turned on after hours. Lastly, occupancy sensors will allow controlling the actual number of occupants and their location.

There must be different access levels to the data according to the user who consults them. On the one hand, managers will be responsible for making decisions, and experts will be in charge of analysis. On the other hand, users will be allowed to participate in the change of habits.

3.2. EPCC IS design

An IS adapted to the EPCC building has been designed. It covers monitoring, communications, storage and visualization. Its parts are explained hereafter (Fig. 4).

3.2.1. EPCC back-end

The virtual machines and servers are hosted in the EPCC. The static data storage obtained in phase 1 has been carried out on the Neo4J database (Neo4j, 2021). It uses a graph as a model to capture the spatial organization of the physical environment, whose nodes are labeled: classroom - floor - building... That way, both the nodes and the edges joining them store sets of key-value pairs called attributes or properties. Its goal is to store more information about the nodes and the existing relationships between them and to connect from there with the other ISs linked to the data typologies described above. Because the nodes of a network are interconnected through links or edges, queries in these databases are quite simple, in contrast with relational models, which can be very costly. In a network, the information is intrinsically connected due to the nature of the data structure (Fig. 5).

Moreover, dynamic time series of sensor data are stored in a specific database, InfluxDB (InfluxData, 2019). It is an open source time series. It is optimized for storage and retrieval of consecutive data indexed to a timestamp, produced by measurement devices. It also allows easy integration with the visualization tool for time series data; in this case, Grafana (Grafana Labs, 2020), that is an open and free software.

In the IS, there is a database called sensors, where there is a value for each of the sensors that make up the physical world network. The information sent by the sensor is organized by columns. Consequently, a consumption sensor will have a column with the timestamp of each measurement and a column with the consumption reading.

3.2.2. EPCC service bus

Data are acquired through a single enterprise service bus, Zato ESB ("Zato Service Bus," 2021). It is an open-source software with commercial and community support written in Python language. It is used to build middleware and back-end systems where they store services for different purposes. The number of data capture devices used was considerable. However, thanks to these services, it has been possible to write the data generated in the databases and the requests in a simple way.

A service in Zato can expose an API and consume data from other internal or external services. Conceiving the overall system functionality as divided into multiple small or very small (micro) services is necessary to take full advantage of this technology. In addition, these services must have little interconnection or coupling between them. The services created are maintained by Zato, monitored and hosted on several redundant servers, which increases the level of stability of the system without development cost. There are other ESBs written in Java in the market. Although ESBs serve large corporations and some of them offer community licenses, many of their most key functionalities are restricted.

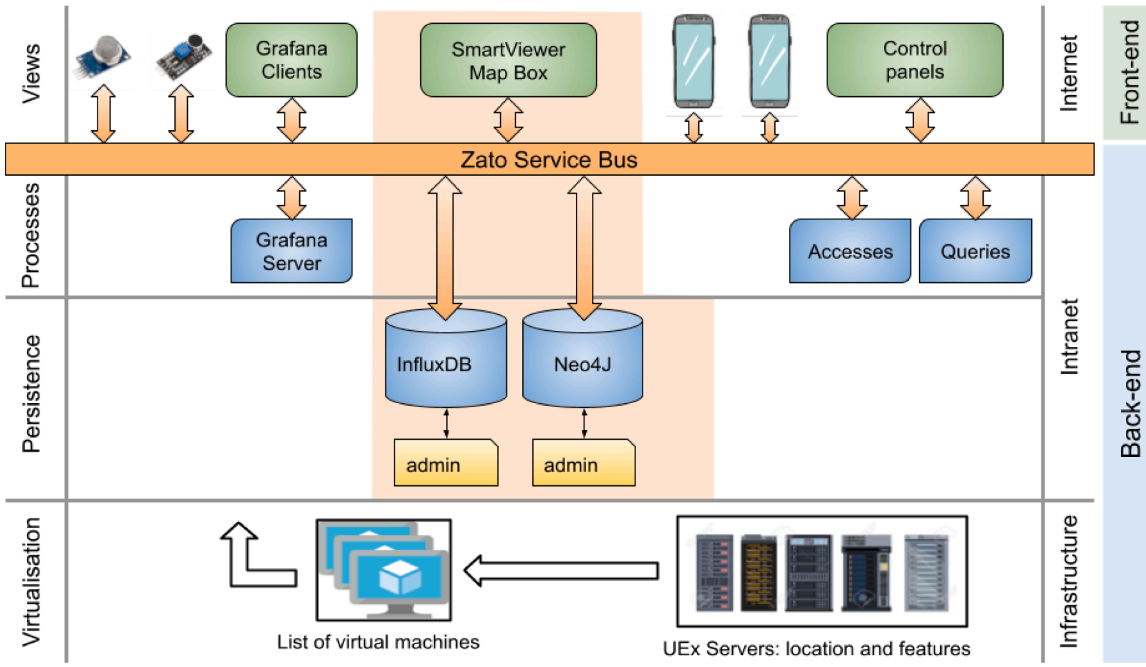


Fig. 4. EPCC IS.

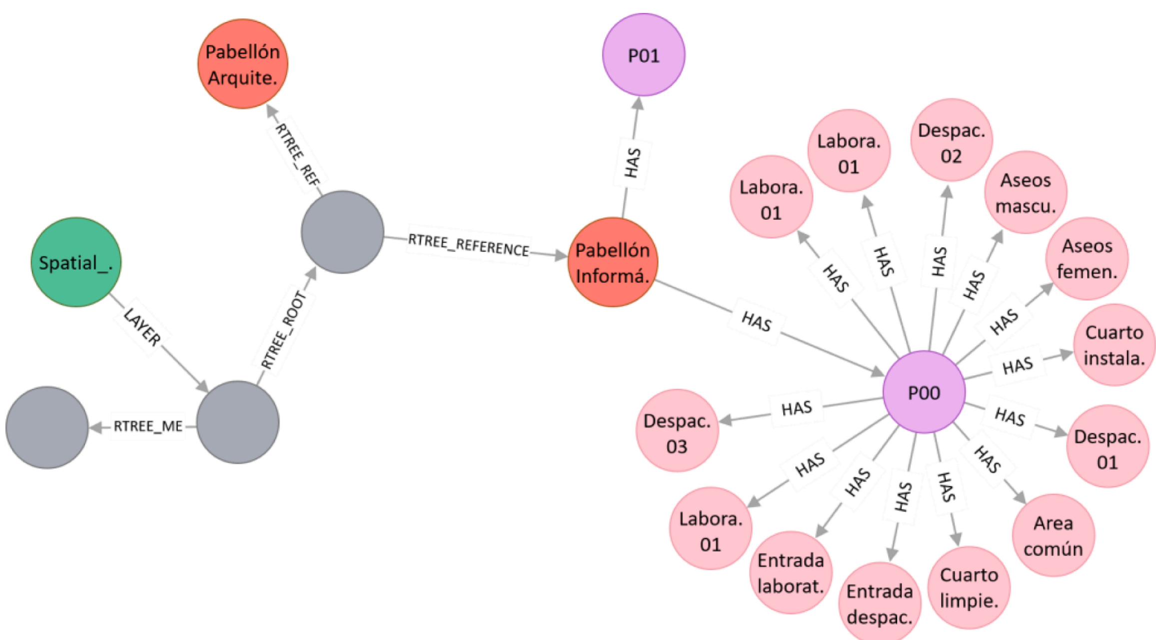


Fig. 5. Neo4J database graph.

3.2.3. *EPCC front-end*

The devices access one of the services available on the service bus to send the information to the databases. When using the REST API offered at the reference address http://smartpolitech-services.unex.es:xxxx, the data is organized according to the JSON format with two main fields:

- Info: this structure is formed by the static data that are sent. It consists of an API key field (unique key associated with each sensor) and a device field (unique identifier of each sensor).

- Data: this structure is formed by the dynamic data or physical variables measured by the sensor.

To achieve this objective, the system previously analyzes the relevant factors, taking into account their expansion, distribution, use, location of critical points and selection of devices, either sensors, meters or other devices in the building. Data collection began in 2016 with 83 devices, and it is working today with 139 devices. They measure variables on energy efficiency, thermal comfort and consumption: ambient temperature and relative humidity, CO_2 concentration, electricity consumption, water consumption, status (on/off) of equipment, contribution of renewable energies, temperature of radiators and boiler water supply and return. Some of them have been manufactured at EPCC. Most devices are low cost, wireless, over Wi-Fi and battery-operated. The accuracy range in data collection has also been an important factor to take into account (Table 1).

The availability of real-time consumption data obtained through the

Table 1
Devices of the sensorization network for the dynamic characterization of EPCC.

Trademark/ brand	Communication	Energy supply	Parameter	Accuracy
RAY STH	WiFi (Reading every 30')	2 battery LR14	Temperature Humidity	± 0.5 °C ± 3 %
RAY STC			CO_2	± 3% ppm
EcoWin (self-made)	WiFi (Reading every 30')	Rechargeable lithium battery 18650	Temperature Humidity Windows opening	± 0.5 °C ± 3 % On/Off
Circutor Wibeee	WiFi	85...265 AC (direct from ATS)	Electricity consumption	Voltage 2 % Electricity 2 %
Circutor CVM-B150	ModBus Rs-485 with runway ModBus/TPC	85...265 AC/ 120...300 DC	Voltage Active energy Reactive energy Frequency	± 0.2 ± 0.5S ± 1 ± 0.1
B-Meters GMDM-I IWM-PL3	By pulses	Non-replaceable lithium battery	Water consumption	10 l/pulse
Itrón	By pulses	Out of supply	Gas consumption	0.1 m^3/ pulse
Circutor LM25-M	ModBus Rs-485 with runway ModBus/TPC	85...265 AC/ 120...300 DC	ModBus pulse centralizer	1 pulse

sensors allows replacing invoice values. These invoices have been helpful to validate consumptions; however, they are limited to monthly and annual global consumptions. Therefore, a more detailed analysis in shorter reading intervals can be performed, and besides it is possible to delimit in which pavilion or specific area of the building those incidents occur.

The location of the sensors has been established considering the representativeness of the data, building a dense network that captures data from the entire EPCC. Thus, sensors have been placed taking into account the orientation of the rooms (due to solar radiation) or the floor height (due to air stratification). They have also been distributed according to the use of each zone, since it determines different activity, metabolism and occupancy. Depending on the dimension chosen, visualization is carried out on two different types of viewers:

- Temporarily: real-time visualization panels have been generated through the Grafana data server connected to the database. These panels are publicly visible, with series stored in multiple configurations and combinations and with data visualization in variable time periods (some examples in Fig. 6). The panels are displayed as a carousel and are visible on the screens distributed throughout the EPCC.

- Spatially: the visualization is done through the specific web viewer developed in this project. The viewer uses Leaf.js and Mapbox open libraries for georeferenced visualization. The different devices and elements that produce data are added on top of the maps. Each type of device is linked to a specific type of visualization to facilitate its interpretation by the end user (Fig. 7).

3.3. EPCC diagnosis and strategies definition

Thanks to the data obtained in the IS, the initial preliminary evaluation towards a definitive diagnosis has been developed. Data visualization screens are equipped with graphs adapted to the building manager (some examples in Fig 7 to 10). Moreover, indicators to facilitate the analysis of the current status and the subsequent planning and monitoring of strategies have been defined (Table 2). Screens and indicators extend the precision and knowledge provided by the analyses performed through invoices.

As measurements started at the end of 2016, some improvements in building performance can be attributed to the monitoring follow-up being performed. The study starts with complete annual data from 2017 and ends in 2019 (Table 2). 2020 and 2021 are discarded for the already stated reason: the global pandemic.

The diagnosis allowed the definition of strategies that can be solved through the next phase. The control and action system is also laid out. Their proposals should be preferably passive and with a social inmotics base. The diagnosis has been carried out in the following areas (Table 2):

- Sensors and system variables: this indicator has continued to grow from one year to the next, as has the average number of records for each variable. It only decreased slightly in the last year analyzed. It can be deduced that the IS makes the model increasingly reliable. There is a lack of occupancy control by monitoring the number and distribution of occupants. This measurement would help to link consumption to activity.
- Electricity consumption indicators: the overall annual decrease and pattern are repeated. In the last three years, the average consumption drops from the previous value of six years of invoices (from 711 MWh to 592 MWh). The monthly average per person is maintained, proving that consumption is proportional to the number of students (32.3 kWh/p on average in this period). However, the consumption decreases from 5.4 to 3.9 MWh/(m^2/p) with respect to the occupancy density.

The equipment sensors provide information on those that are still on outside working hours. The annual average of the non-occupancy hours in which the equipment is still on is 38%.

The analysis is extended to each pavilion in the graphs, as well as to smaller time regimes. It is found that the hourly pattern is repeated: maximum consumption occurs from 9 a.m. to 1 p.m., coinciding with the periods of highest occupancy of classes; in contrast, the lowest consumption is measured on weekends, and in the winter months. Although there are differences between the pavilions, the one that consumes the most hosts the largest number of students and equipment. The second highest consumption is registered in the pavilion that houses a large part of the servers of the research groups and, therefore, of the cooling equipment. The high consumption bases previously detected above are located in this pavilion (section 3.1.3). These bases consume 10 and 15

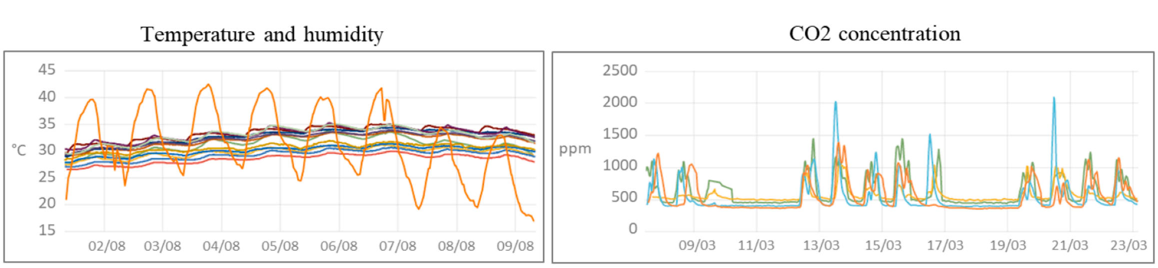


Fig. 6. Examples of Grafana display panels from the EPCC with temporary data on electricity and water consumption, temperature and humidity and CO_2 concentration.

Fig. 7. Viewing EPCC spatial data in Mapbox.

Table 2
Data indicators and statistical metrics: general, consumption and IEQ parameters.

	INDICATORS	2017	2018	2019	Mean (standard deviation)
GENERAL	No. of water/electricity/temperature & humidity/CO2/equipment	12/18/46/4/	14/28/45/4/33	13/30/53/4/33	13/25/48/4/22
	sensors	0	130 / +56 % ↑	139 / +7 % ↑	117
	Total no. of system sensors/ evolution (1)	83 / -	182 / +1037 % ↑	248 / +36 % ↑	149
	Total no. of system variables/ evolution (1)	16 / -	2251177/ +139%	2035685/-10%	1742545
	Mean no. of records per variables/ evolution (1)	940775 / -	↑	↓	
CONSUMPITION	Annual electricity (MWh)/ evolution (1)	653	581 ↓	542 ↓	592 (56.2)
	Monthly mean electricity (kWh/m^2)/(kWh/p)/(MWh/(m^2/p))/ evolution (1)	2.8/ 33.4/ 4.5	2.5/ 31.8/ 3.8 ↓	2.3/ 31.6/ 3.3 ↓	2.5/ 32.3/3.9
	No. of hours with connected devices after working hours (3)	-	46296	57362	51829/7824
	No. of total measurements hours (3)	-	115962	160677 ↑	138320/31618
	Percentage of hours of connected devices/ evolution (1)	-	40 %	36 % / -4 % ↓	38 %
	Annual water (m3)/ evolution (1)	2105	1228 ↓	1178 ↓	1503/522
	Monthly mean water (l/p), daily average (l/p)	107.8/ 3.6	67.2/ 2.2 ↓	68.7/ 2.3 ↑	81.2/2.7
	Annual natural gas (MWh) (4)/ evolution (1)	836	1048 ↑	1016 ↓	967/114
	Monthly mean natural gas (kWh/m^3) / (kWh/p) / (MWh/(m^2/p)) (4)	1.9/73.5/ 10.9	2.8/ 98.3/ 12.8 ↑	2.3/101.6/11.6 ↓	2.3/ 91.1/11.8
IEQ (5)	No. of hours in thermal discomfort in winter (<21 °C)	37367	46044	42779	42063/4383
	No. of total measurements hours (collected by sensors)	57774	63015 ↑	62688 ↓	61159/2936
	Percentage of hours in thermal discomfort in winter/ evolution (1)	65 % / -	73 % / +8 % ↑	68 % / -5 % ↓	69 %
	No. of hours in thermal discomfort in summer (>25 °C)	40978	25128	39329	3514/8714
	No. of total measurements hours (collected by sensors)	61391	54328 ↓	68293 ↑	61337/6982
	Percentage of hours in thermal discomfort in summer/ evolution (1)	67 % / -	46 % / -20 % ↓	58 % / +11 % ↑	57 %
	No. of hours in humid discomfort (<30 o >70 %)	55625	41461	61500	5286/10301
	No. of total measurements hours (collected by sensors)	147840	146076 ↓	168588 ↑	154168/12519
	Percentage of hours in humid discomfort/ evolution (1)	38 %	28 % / -10 % ↓	36 % / +8 % ↑	34 %
	No. of data with poor air quality (CO2 >1000 ppm)	996	1005	824	932/102
	No. of total valid measurements hours (collected by sensors)	11604	9443	8387	9811/1639
	Percentage of hours with poor air quality/ evolution(1)	8 % / -	11 % / 3 % ↑	10 % / 1 % ↓	9.6 %

The occupancy considered is theoretical (enrolled students and workers), no holidays or days when the center is closed have been considered.
↑ ↓ the record is higher or lower than the previous year, red when the evolution is unfavorable, green when this is favorable.
(1) Of each year compared to the preceding year.
(2) Standard deviation is calculated on the annual mean.
(3) Monday to Friday from 10 pm to 8 am, including closed and vacation periods (Christmas, Easter and August).
(4) These data were obtained from invoices and not from sensorization.
(5) Monday to Friday from 8am to 10pm, excluding closing periods and vacations (Christmas, Easter and August). The hourly data corresponds to the mean of data taken in that time slot.

kWh per month, and these levels remain constant every day at any time (Fig. 8).

The strategies are related to the increasing monitoring in a sectorized manner in the two pavilions with the highest consumption base, as this will provide more significant savings. It is proposed to add occupancy sensors in them and increase controlling sensors to switch off equipment outside working hours. Since the outdoor air temperature is usually low enough, another proposal is to reduce cooling consumption in the server room through ventilation.

- Water consumption indicators: data for the last three years show a substantial average annual difference with respect to what is being billed (4,213 m^3 from 2009 to 2015 compared to 1,503 m^3 from 2017 to 2019). This difference can be attributed to major

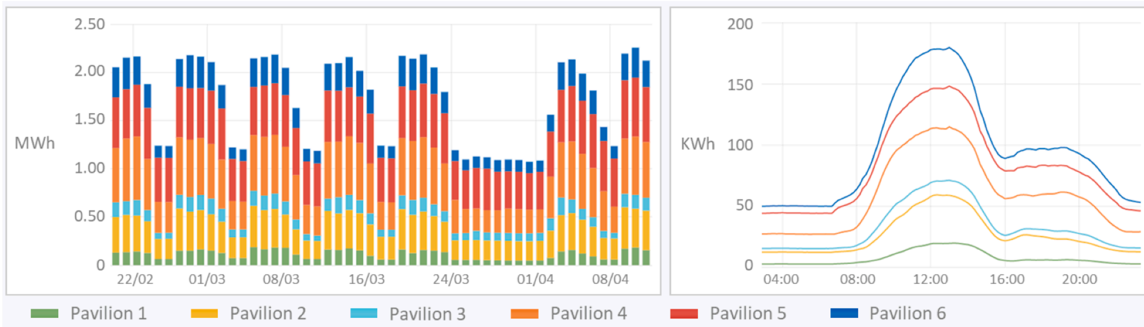


Fig. 8. Examples of Grafana dashboard with visualization adapted to the building manager with data on electricity consumption from monitoring: hourly graphs of 2019 according to buildings, according to months and historical evolution from October 2016 to November 2020.

breakdowns in the campus network that should be repaired. Moreover, consumption decreased by half in the first year with respect to the global indicators. This drop may be due to the alerts and campaigns carried out (section 3.4). The daily average is 2.7 liters of water per person. Peaks are detected from 11 a.m. to 4 p.m., and due to cleaning activity from 6 a.m. onwards. The lowest consumption is measured in August and December, coinciding with the lowest electricity consumption. In contrast, highest consumption occurs in May and October. The pavilion hosting the cafeteria presents the highest water consumption. There is a large difference in overall consumption between the pavilions; however, the consumption per person remains constant. In addition, hidden breakdowns or leaks occur quite frequently, represented in the graph by horizontal lines maintained over time. Monitoring has contributed to locate these incidents in space and in real time (Fig. 9). As a strategy, it is proposed to continue programming alerts to locate and repair water faults in real time.

- Gas consumption indicators: there are no data from sensors. Consequently, the data from invoices focused on the last three years are used again. It is found that the total annual consumption continues to rise. The average is 967 MWh, with a high dispersion of results, indicating a high variability each year. The monthly average also rises (from 1.9 in 2017 to 2.3 kWh/m^3 in 2019). There is no direct correlation between consumption and the greater or lesser severity of winter temperatures. As shown in surveys, users' comfort did not change either. Consumption increased by 25% from 2017 to 2018, as did the discomfort hours. However, 2018 was not colder than the previous year. The same pattern is repeated from 2018 to 2019. It should be noted that the system is not automated, and the heating is manually controlled by the centeŕs clerk.
- Hygrothermal indicators: the comfort range needs to be taken into account. The hygrothermal comfort range, for which the PPD (predicted percentage of dissatisfied) is below 10 %, considers the optimal temperature between 20°C and 24°C in winter, and between 23°C and 26°C in summer (Ministry of Industry Energy and Tourism. Spanish Government., 2007; Technical committee AEN/CTN 100, 2007). Regarding optimal relative humidity, values range between 25 % and 60 % (Technical committee AEN/CTN 100, 2007); or between 30 % and 70 % (Ministry of Industry Energy and Tourism. Spanish Government., 2007), in both seasons. The indicators show that in winter, even with heating systems, 69% of the total average hours' present thermal discomfort (< 21 °C). In summer, thermal discomfort (>25 °C) amounts to 57% of the total average hours. There is no cooling system in the sensorized spaces, nor shading or ventilation systems or awareness in users' habits.

The graphs show a large oscillation between day and night. Temperature lowers on weekends in winter when the heating is turned off. Higher temperatures are measured in the rooms located to the east in the morning and to the west in the afternoon. Air stratification presents higher values on the top floor (Fig. 10). Humidity in the EPCC does not exceed the 70 % limit, but it is sometimes below 20% in the warm period of the year.

The strategy includes an automated system that acts on the radiators' on and off set points depending on the indoor and outdoor environmental operating conditions, occupancy, the feeling of comfort of the users, and weather forecasts, adapting the consumption in every emitting equipment. Regarding summer temperatures, it is necessary to increase night ventilation.

Therefore, it is proposed to install and automate elements of protection and capture of solar radiation in openings by means of blinds, awnings or gratings. In addition, it is necessary to work with human behavior and the acquisition of good habits in the operation of windows and blinds.

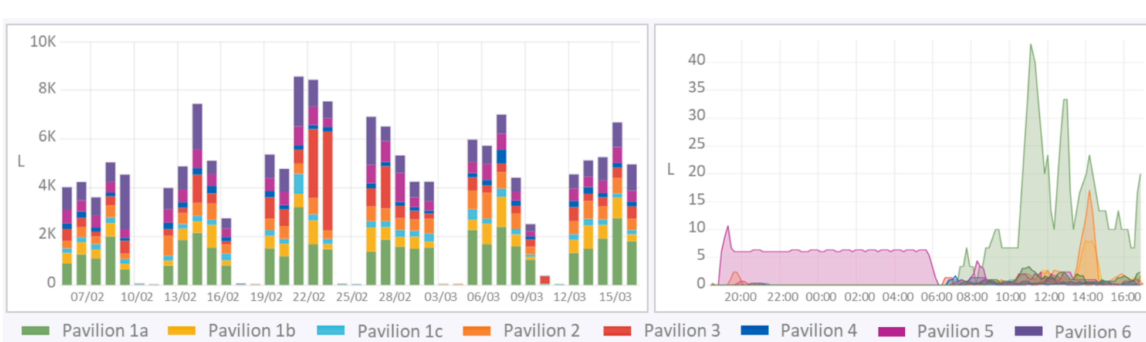


Fig. 9. Examples of Grafana dashboard with visualization adapted to the building manager with data on water consumption from monitoring: graphs by buildings daily, hourly (where a water leakage is displayed) and evolution of the year 2018.

Fig. 10. Grafana dashboard with visualization adapted to the building manager with the evolution of some rooms' temperature of one of the pavilions in 2018 with annual graphs and from winter and summer period (including comfort limits according to (Technical committee AEN/CTN 100, 2007)).

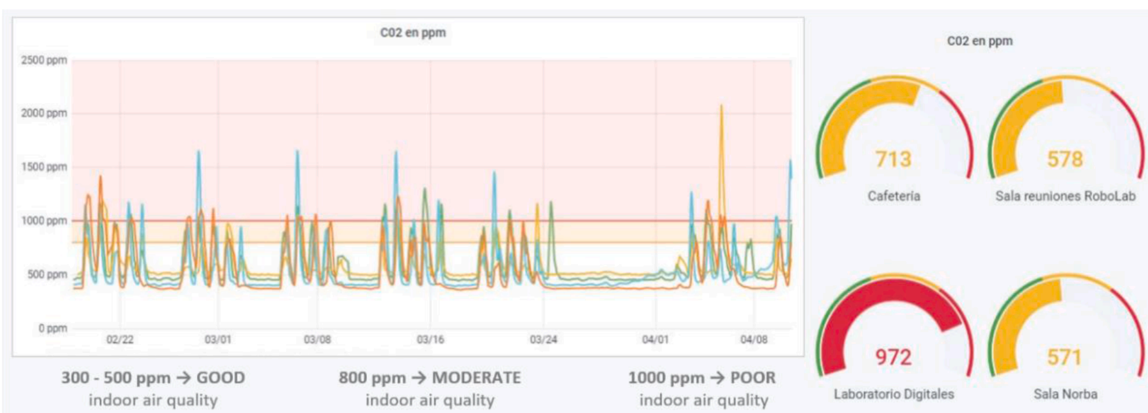


Fig. 11. Grafana dashboard with visualization adapted to the building manager with the evolution of CO_2 concentration in March and April 2018 (including IAQ limits according to (Ministry of Industry Energy and Tourism. Spanish Government., 2007)).

- CO_2 concentration indicators: this with respect to IAQ is considered acceptable at 800 ppm, low at 1000 ppm, and being 1500 ppm the maximum level of comfort conditions (Ministry of Industry Energy and Tourism. Spanish Government., 2007), or 1200 ppm (800 ppm above outdoor conditions) (Technical committee AEN/CTN 100, 2007). EPCC has only four sensors installed: two in classrooms, one in a meeting room and the last one in the cafeteria. During the three years analyzed, an average of 9.6 % of the occupied hours exceeded the 1000 ppm concentration.

In addition, significant infiltrations can be seen in the sharp peaks of the graph. The periods of highest concentration correspond to class hours. Without ventilation actions, the concentration drops sharply to the base value of 380 ppm (

The proposed strategy is to install a mechanical ventilation system that allows the renewal of indoor air through the set points generated by the CO_2 meters. It also calls for raise user's awareness through the system.

3.4. EPCC control and actuation system design

The control and actuation systems that have been implemented respond to the strategies described in the previous section. The strategies advocate awareness campaigns to enhance user's participation. Actuators in the form of alerts, alarms, valves and gratings have also been included. Following these actions, new indicators have been obtained. All these measures will continue to allow validation in the iteration of the method.

The average annual number of interactions on Twitter is 439, and the trend goes upward each year. In addition, the average annual number of people participating in the campaigns is 279. The average number of annual water alerts is 1454 (Table 3).

3.4.1. Campaigns

On the one hand, data visualization boards have been displayed on screens located in common areas (Image 1, Fig. 12). Boards have been presented in a simple, visual way and in real time. Information has been adapted to all users (Image 2, Fig. 12). On the other hand, messages have been spread thanks to social networks. In addition, surveys with QR codes have been carried out. Both resources have used awareness and persuasion techniques to encourage participation and change of habits towards building efficiency. The following campaigns have been carried out:

Table 3
Data indicators and statistical metrics: campaigns and alerts.

	INDICATOR / PARAMETER	2017	2018	2019	Mean
CAMPAIGNS	No. of interactions on twitter/ evolution [(1)]	241	381/ +58% ↑	695/ +82% ↑	439
	No. of people participating in campaigns/ evolution [(1)]	187	354/ +89% ↑	295/ -17% ↓	279
ALERTS	No. of water alerts/ evolution [(1)]	106 (from 05/12/ 17)	1482	1,427/ -4% ↓	1,454 [(1)]

↑ ↓ The record is higher or lower than previous year, red when the evolution is unfavorable, green when it is favorable.
[(1)] Of each year compared to the preceding year.
[(2)] Only the last two years have been taken into account.

- Electricity consumption: tweets showing the renewable energy captured in the photovoltaic panels, and the contribution to the building were published (Tweet 1, Fig. 2).
- Water consumption: wheel graphs with red/green scales according to today's overall consumption compared to yesterday's were displayed. Graphs also have information on personal daily consumption to encourage individual action (Image 2, Fig. 12) Tweets with real-time consumption messages of some events and breakdowns were sent as well (Tweet 2, Fig. 2).
- Hygrothermal comfort: through 3D images of the buildings with indoor and outdoor environmental data in real time for each sensorized room, as well as information on the comfort ranges according to the climatic period (Image 3, Fig. 12); and through tweets recommending the operation of the blinds according to each period of the year (Tweets 3 and 4, Fig. 13), as well as comfort surveys with QR codes.
- CO_2 concentration: scale wheels of different colors were used. They included messages on air quality and pieces of advice on ventilation (Image 4, Fig. 12).

3.4.2. Actuators

- Waer alerts: as of December 5th, 2017, an action protocol with water consumption alerts was designed and implemented in Grafana. It detects a higher value than usual during a certain period in any of the buildings. It sends a warning via email and Telegram to the EPCC clerks. This has improved response times to breakdowns and failures in the supply system. The annual evolution of water consumption is decreasing (section 3.3) since this alert exists, the most common cases occur with open toilet tanks (example of failure in Fig. 9). In the same way, other alerts can be programmed with respect to electrical, gas consumption or discomfort.
- Thermostatic radiator valves: they were installed in the radiators of the highest occupancy pavilion (MClimate Vicki LoRaWAN). These smart thermostatic radiator valves control and monitor temperature individually in each space from a distance. Their heating power can be adjusted separately. Depending on the metabolic activity calculated in each space adaptive comfort parameters have been programmed adjusting the opening of the valves and optimizing energy consumption.

3.5. Iterative system optimization

As a result of the first iteration of the methodology, a prototype has been proposed and is being developed. It consists of a smart system for control and automation. The analysis of data allows the algorithms implementation in the control system which activates the adequate heating operation. The prototype is currently being designed to improve indicators regarding energy savings, thermal comfort and air quality, and adjustment of occupancy and operation. Therefore, the automation and prior monitoring system will control the building operation and act on the facility.

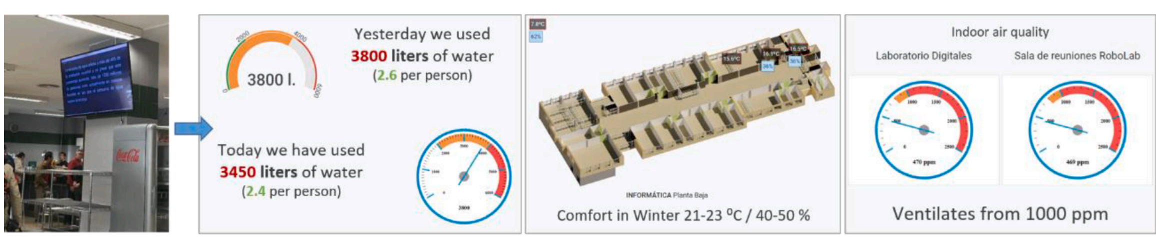


Fig. 12. Data visualization board in a public space on EPCC and Grafana dashboards adapted to general user: visualization of water consumption, comfort and IAQ data.

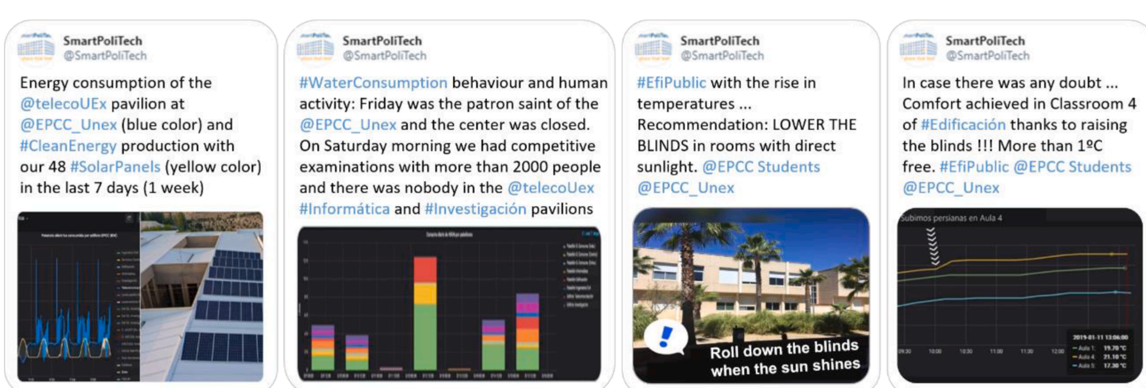


Fig. 13. Examples of campaign messages on social networks: electricity and water consumption and IEQ parameters.

Once the prototype is finished, the existing information will be expanded. New sensors and actuators could be added to the system. Together with the existing ones, these devices would incorporate new environmental and consumption data to the InfluxDB and Neo4j databases. That way, they complete the available information that will be subsequently visualized through Grafana. In addition, new visualizations will be designed on this website. Moreover, new accesses and processes will be incorporated into the Grafana server (phase 3). The building will be diagnosed again. New indicators will be obtained, and they will help analyze how the system is working. New strategies will be then generated from these indicators (phase 4). Thanks to this procedure, it will be possible to validate the implemented system and make proposals for control and actuation (phase 5). Once these proposals are introduced, they will reiterate the third and successive rounds of the methodology.

4. Conclusion

The experience obtained in the application of this methodology represents a step forward introducing automation in existing buildings towards their transformation into smart ones, and with this, the adaptation and resilience of the building stock towards the current requirements of decarbonization. Thus, at present, the building performance is being gradually optimized through the application and validation of improvement strategies by using information technologies in maintenance and management of in-use facilities.

The main theoretical and practical implications of the methodology are the following:

- Implementing social inmotics to promote a correct interaction of the building with its users, training them to reduce both the consumption of natural resources, and greenhouse gas emissions as well as, to improve IEQ. Likewise, occupants' involvement has been encouraged thus some of them have changed their habits according to their user profile. Learning the correct habits in public buildings enhances subsequent application to the private sphere, and therefore to the domestic one as well. In this way, social inmotics is employed as the way to control and manage integral building automation by the users themselves.

- Monitoring in real time is considered essential; so that, any query according to any conditions can be made.
- The correct choice of the monitoring devices, the software for a correct flow data, and the structure of the IS are necessary to guarantee the projection of results in the future.
- The prior characterization and evaluation of the building and its users is considered fundamental for the proper customized design of the IS, which should strongly serve as a basis for any further extension of the system.
- Developing the case study in a campus allows for continuous improvement in a progressive manner by using it as a prototype for research, but the findings could be applied to any other building.
- Using key performance indicators measuring and continuously validating the strategies' implementation as well as optimizing the methodology effectiveness is successfully supporting the decision making.
- The IS must be scalable (which can be implemented in part or whole buildings at the urban level towards smart city or smart territory, as well as continuously adapting to new technologies and/or situations), adaptable (according to needs in time, use and/or existing regulations at any given moment), incremental (in each iteration) and open source (without dependence on any proprietary system),
- This methodology can be used in any existing building (regardless of the type of use and size), and any environmental conditions with other requirements (variables such as solar radiation, noise, polluted outdoor air, etc.) with a low-cost investment. Although some of the procedures, like installation of sensors and actuators, databases integration, visualization design or general processes follow-up, require human resources; they are in continuous evolution and some of them will be made automatically in a near future.
- It can be applicable by users who are not familiar with reading graphs due to the fact that dashboards can be designed with visualization adapted to different usage profiles.

As future work, in the final version of the methodology, the adjusted building model could be connected to specific simulators to evaluate different situations, and to prediction models through machine learning in artificial intelligence, using for example digital twins.

One issue to keep in mind is that, in future climate change, the energy demand profiles, which were not accounted for in the initial design of the buildings, will significantly vary. In this way, systems will have to be readapted necessarily, an action that can be carried out by applying this methodology. Furthermore, these updated indicators may be used by any Administrations or building managers to compare the efficiency of public or private buildings and make decisions in order to address urban regeneration and adaptation to climate change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research has been made possible thanks to the projects: SMARTPOLITECH UNEX13-1E-1716 (Intelligent energy efficiency system for the School of Technology), from the Infrastructures call of the Ministry of Economy and Competitiveness (2013-2016); EFIPUBLIC IB16128 (Social immotics for the efficient use of public buildings), from the call for Research Projects in Public R&D&I Centres, from the Ministry of Economy and Infrastructures of the Regional Government of Extremadura and the European Regional Development Fund of the EU (2017-2020); and INNOINVEST 0605_INNOINVEST_4_E (Promotion of business investment in innovation of energy products for buildings), of the Operational Programme EP-INTERREG V A Spain Portugal (POCTEP) (2019- 2021). This publication has been translated thanks to funding granted by the Ministry of Economy, Science, and Digital Agenda from the Regional Government of Extremadura and by the European Regional Development Fund of the EU through the reference grant GR18032.

References

Ahmad, M. W., Mourshed, M., Mundow, D., Sisinni, M., & Rezgui, Y. (2016). Building energy metering and environmental monitoring – A state-of-the-art review and directions for future research. *Energy and Buildings, 120*, 85–102. https://doi.org/10.1016/J.ENBUILD.2016.03.059

Alam, K. M., & El Saddik, A. (2017). C2PS: A digital twin architecture reference model for the cloud-based cyber-physical systems. *IEEE Access, 5*, 2050–2062. https://doi.org/10.1109/ACCESS.2017.2657006

Alghamdi, A., & Shetty, S. (2016). Survey toward a smart campus using the internet of things. In *Proceedings - 2016 IEEE 4th International Conference on Future Internet of Things and Cloud, FiCloud 2016* (pp. 235–239). https://doi.org/10.1109/FiCloud.2016.41

Allab, Y., Pellegrino, M., Guo, X., Nefzaoui, E., & Kindinis, A. (2017). Energy and comfort assessment in educational building: Case study in a French university campus. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2016.11.028

Almeida, L. M. M. C. E., Tam, V. W. Y., & Le, K. N. (2021). Users' building optimal performance manual. *Cleaner and Responsible Consumption, 2, 100009*. https://doi.org/10.1016/j.clrc.2021.100009

Álvarez, M., Raposo, J. F., Miranda, M., Bello, A. B., & Barbero, M. (2019). Desarrollo del SmartCampus de Montegancedo (UPM) basado en el modelo de las Infraestructuras de Datos Espaciales. *Informes de La Construcción, 71*(555), 307. https://doi.org/10.3989/ic.66252

American Society of Heating and Air-Conditioning Engineers (ASHRAE). (2020). *2020 ASHRAE Handbook Systems and Equipment*. Retrieved from https://www.ashrae.org/about/news/2020/2020-ashrae-handbook-focuses-on-systems-and-equipment.
Aslam, S., Iqbal, Z., Javaid, N., Khan, Z., Aurangzeb, K., & Haider, S. (2017). Towards Efficient Energy Management of Smart Buildings Exploiting Heuristic Optimization with Real Time and Critical Peak Pricing Schemes. *Energies*, 10. https://doi.org/10.3390/en10122065. https://doi.org/doi.org/.
Bamodu, O., Xia, L., & Tang, L. (2017). An indoor environment monitoring system using low-cost sensor network. *Energy Procedia, 141*, 660–666. https://doi.org/10.1016/J.EGYPRO.2017.11.089
Bonci, A., Carbonari, A., Cucchiarelli, A., Messi, L., Pirani, M., & Vaccarini, M. (2019). A cyber-physical system approach for building efficiency monitoring. *Automation in Construction, 102*, 68–85. https://doi.org/10.1016/j.autcon.2019.02.010
Buitelaar, E., Moroni, S., & De Franco, A. (2021). Building obsolescence in the evolving city. Reframing property vacancy and abandonment in the light of urban dynamics and complexity. *Cities, 108*, Article 102964. https://doi.org/10.1016/j.cities.2020.102964
Burgas, L., Melendez, J., Colomer, J., Massana, J., & Pous, C. (2015). Multivariate statistical monitoring of buildings. Case study: Energy monitoring of a social housing building. *Energy and Buildings, 103*, 338–351. https://doi.org/10.1016/j.enbuild.2015.06.069
Cao, X., Dai, X., & Liu, J. (2016). Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. *Energy and Buildings, 128*, 198–213. https://doi.org/10.1016/j.enbuild.2016.06.089
Chaudhari, N., Bhadoria, R. S., & Prasad, S. (2017). Information Handling and Processing Using Enterprise Service Bus in Service-Oriented Architecture System. *Proceedings - 2016 8th International Conference on Computational Intelligence and Communication Networks, CICN 2016*, 418–421. https://doi.org/10.1109/CICN.2016.88
Ciuffoletti, A. (2018). Low-Cost IoT: A Holistic Approach. *Journal of Sensor and Actuator Networks, 7*(2), 19. https://doi.org/10.3390/jsan7020019
D'Agostino, D., Cuniberti, B., & Bertoldi, P. (2017). Energy consumption and efficiency technology measures in European non-residential buildings. *Energy and Buildings, 153*, 72–86. https://doi.org/10.1016/J.ENBUILD.2017.07.062
European Commission. (2016). Urban agenda for the EU. Retrieved April 28, 2021, from https://ec.europa.eu/info/eu-regional-and-urban-development/topics/cities-and-urban-development/urban-agenda-eu_es.
European Commission. (2020). 2 050 long-term strategy | Climate Action. Retrieved May 6, 2021, from https://ec.europa.eu/clima/policies/strategies/2050_en.
Eurostat. (2020). *Energy, transport and environment statistics — 2020 edition - Products Statistical Books*. Retrieved from https://ec.europa.eu/eurostat/en/web/products-statistical-books/-/ks-dk-20-001.
Federation of European Heating, V. and, & Air Conditioning Associations (REHVA). (2019). *REHVA Guidebook 29 Improving Building Performance through Technical Monitoring and Commissioning*. Retrieved from https://www.rehva.eu/hvac-guidebook-repository/rehva-guidebook-29.
Fernández-Caramés, T. M., & Fraga-Lamas, P. (2019). Towards next generation teaching, learning, and context-aware applications for higher education: A review on blockchain, IoT, Fog and edge computing enabled smart campuses and universities. *Applied Sciences (Switzerland)*, (21), 9. https://doi.org/10.3390/app9214479
Fortes, S., Santoyo-Ramón, J., Palacios, D., Baena, E., Mora-García, R., Medina, M., …, & Barco, R. (2019). The Campus as a Smart City: University of Málaga Environmental, Learning, and Research Approaches. *Sensors, 19*(6), 1349. https://doi.org/10.3390/s19061349
Gilman, E., Tamminen, S., Yasmin, R., Ristimella, E., Peltonen, E., Harju, M., …, & Pirttikangas, S. (2020). Internet of Things for Smart Spaces: A University Campus Case Study. *Sensors, 20*(13), 3716. https://doi.org/10.3390/s20133716
Grafana Labs. (2020). The leading open source software for time series analytics. Retrieved December 29, 2019, from http://grafana.org.
Hong, T., Yan, D., D'Oca, S., & Chen, C (2017). Ten questions concerning occupant behavior in buildings: The big picture. *Building and Environment, 114*, 518–530. https://doi.org/10.1016/J.BUILDENV.2016.12.006
InfluxData. (2019). InfluxDB. Retrieved December 29, 2019, from https://docs.influxdata.com/influxdb/v1.7/.
Instituto de Ciencias de la Construcción y Consejo Superior de Investigaciones Científicas. (n.d.). Monitorización y evaluación de la habitabilidad, calidad del aire y eficiencia energética de los edificios. Experiencias en España (2020th ed.).
International Energy Agency. (2020). Buildings. Retrieved May 6, 2021, from https://www.iea.org/topics/buildings.
Dakheel, Joud Al, Pero, Claudio Del, & Niccol`oAste, F. L (2020). Smart Buildings Features and Key Performance Indicators: A Review. *Sustainable Cities and Society, 105919*. https://doi.org/10.1016/j.jeconbus.2020.105919
Khalid, A., Javaid, N., Guizani, M., Alhussein, M., Aurangzeb, K., & Ilahi, M. (2020). Towards Dynamic Coordination Among Home Appliances Using Multi-Objective Energy Optimization for Demand Side Management in Smart Buildings. *IEEE Access, 6*. https://doi.org/10.1109/ACCESS.2018.2791546
Khoshbakht, M., Gou, Z., & Dupre, K. (2018). Energy use characteristics and benchmarking for higher education buildings. *Energy and Buildings, 164*, 61–76. https://doi.org/10.1016/J.ENBUILD.2018.01.001
Kim, J., Hong, T., Kong, M., & Jeong, K. (2020). Building occupants' psycho-physiological response to indoor climate and CO2 concentration changes in office buildings. *Building and Environment, 169*, Article 106596. https://doi.org/10.1016/j.buildenv.2019.106596
Langevin, J., Gurian, P. L., & Wen, J. (2015). Tracking the human-building interaction: A longitudinal field study of occupant behavior in air-conditioned offices. *Journal of Environmental Psychology, 42*, 94–115. https://doi.org/10.1016/J.JENVP.2015.01.007
Martins, P., Lopes, S. I., da Cruz, A. M. R., & Curado, A. (2021). Towards a smart & sustainable campus: An application-oriented architecture to streamline digitization and strengthen sustainability in academia. *Sustainability (Switzerland), 13*(6), 3189. https://doi.org/10.3390/su13063189
Melzi, F. N., Same, A., Zayani, M. H., & Oukhellou, L. (2017). A dedicated mixture model for clustering smart meter data: Identification and analysis of electricity consumption behaviors. *Energies, 10*(10), 1446. https://doi.org/10.3390/en10101446
Ministerio de Fomento Gobierno de España. (2017). *Estrategia a largo plazo para la rehabilitación energética en el sector de la edificación en España ERESEE 2017*. Madrid.
Ministry of Industry Energy and Tourism. Spanish Government. (2007). *Regulation of Thermal Installations in Buildings., 207*. BOE. de 29/08/2007 Sec 1 §.
Montalbán Pozas, B., Amigo Gamero, I., Domínguez Sánchez, A., & Bustos García De Castro, P. (2020). A methodology to improve energy efficiency and comfort conditions with low-cost ICTs in rural public buildings. *Sustainable Cities and Society, 102156*. https://doi.org/10.1016/j.scs.2020.102156. https://doi.org/https://doi.org/.
Montalbán Pozas, B., Bustos García de Castro, P., Barrena García, M., Sánchez Domínguez, A., García Rodríguez, P., Del Río Pérez, M, & University of Cantabria. (2018). Improving energy efficiency in public buildings through social inmotics. *Rehabend 18, Construction Pathology*. Cáceres: Rehabilitatiion Technology and Heritage Management.
Neo4j, I. (2021). Neo4j. Retrieved December 29, 2019, from https://neo4j.com/.
Núñez, P., Barroso, S., Muriel, B., Lucas, M., Montalbán, B., & Bustos, P. (2020). Sistema de información del sistema Cyber-Físico SmartPoliTech. *Monitorización y evaluación de la habitabilidad*. calidad del aire y eficiencia energética de los edificios, 2020th ed., pp. 49–58.
Pan, S., Wang, X., Wei, S., Xu, C., Zhang, X., Xie, J., … de Wilde, P. (2017). Energy waste in buildings due to occupant behaviour. *Energy Procedia*, 105, 2233–2238. https://doi.org/10.1016/J.EGYPRO.2017.03.636.
Papantoniou, S., Mangili, S., & Mangialenti, I. (2017). Using Intelligent Building Energy Management System for the Integration of Several Systems to one Overall Monitoring and Management System. *Energy Procedia, 111*, 639–647. https://doi.org/10.1016/j.egypro.2017.03.226
Park, J. Y., Ouf, M. M., Gunay, B., Peng, Y., O'Brien, W., Kjærgaard, M. B., & Nagy, Z. (2019). A critical review of field implementations of occupant-centric building controls. *Building and Environment, 165*, Article 106351. https://doi.org/10.1016/J.BUILDENV.2019.106351
Priyanka Jain, A. G. (2018). Review of IoT Market and Open Source Technologies in IoT. *International Journal of Engineering Research in Computer Science and Engineering (IJERCSE), 5*(2), 0–5.
Sanchez, A. S., & Oliveira, K. P. S. (2018). Internet of Things for a Smart Campus On Line Monitoring of Water Consumption in University Buildings. *International Journal of Engineering Research And, V7*(03). https://doi.org/10.17577/ijertv7is030187
Sharmin, T., Gül, M., Li, X., Ganev, V., Nikolaidis, I., & Al-Hussein, M. (2014). Monitoring building energy consumption, thermal performance, and indoor air quality in a cold climate region. *Sustainable Cities and Society, 13*, 57–68. https://doi.org/10.1016/J.SCS.2014.04.009
Stazi, F., Naspi, F., & D'Orazio, M (2017). A literature review on driving factors and contextual events influencing occupants' behaviours in buildings. *Building and Environment, 118*, 40–66. https://doi.org/10.1016/J.BUILDENV.2017.03.021
Stopps, H., & Touchie, M. F. (2020). Managing thermal comfort in contemporary high-rise residential buildings: Using smart thermostats and surveys to identify energy efficiency and comfort opportunities. *Building and Environment, 173*. https://doi.org/10.1016/j.buildenv.2020.106748
Sun, K., & Hong, T. (2017). A simulation approach to estimate energy savings potential of occupant behavior measures. *Energy and Buildings, 136*, 43–62. https://doi.org/10.1016/j.enbuild.2016.12.010
Technical committee AEN/CTN 100. (2007). *UNE-EN 15251:2008. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*.
The European Parliament and the Council of the European Union. *Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy*., (2000).
The European Parliament and the Council of the European Union. *Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency*., (2018).
Vellei, M., Natarajan, S., Biri, B., Padget, J., & Walker, I. (2016). The effect of real-time context-aware feedback on occupants' heating behaviour and thermal adaptation. *Energy and Buildings, 123*, 179–191. https://doi.org/10.1016/J.ENBUILD.2016.03.045
Wang, L., & Zheng, D. (2020). Integrated analysis of energy, indoor environment, and occupant satisfaction in green buildings using real-time monitoring data and on-site investigation. *Building and Environment, 182*, Article 107014. https://doi.org/10.1016/j.buildenv.2020.107014
Xiao, F., & Fan, C. (2014). Data mining in building automation system for improving building operational performance. *Energy and Buildings, 75*, 109–118. https://doi.org/10.1016/J.ENBUILD.2014.02.005
Zato Service Bus. (2021). Retrieved April 28, 2021, from https://zato.io/.