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IoB Internet of Things (IoT) for Smart Built Environment (SBE): Understanding the Complexity and Contributing to Energy Efficiency; A Case Study in Mediterranean Climates

Ignacio Martínez Ruiz [1,*], Enrique Cano Suñén [1], Álvaro Marco Marco [1,2] and Ángel Fernández Cuello [1]

[1] Human OpenWare (HOWLab), Engineering Research Institute of Aragon (I3A), University of Zaragoza (UZ), 50018 Zaragoza, Spain; ecs@unizar.es (E.C.S.); amarco@unizar.es (Á.M.M.); afernan@unizar.es (Á.F.C.)
[2] Academia General Militar, Centro Universitario de la Defensa, 50090 Zaragoza, Spain
* Correspondence: imr@unizar.es

Featured Application: Applying this work in public buildings allows energy savings by minimizing time when temperatures are above 21 °C with heating on while guaranteeing user thermal comfort.

Abstract: To meet the 2050 targets about climate change and decarbonization, accomplishing thermal comfort, Internet of Things (IoT) ecosystems are key enabling technologies to move the Built Environment (BE) towards Smart Built Environment (SBE). The first contributions of this paper conceptualise SBE from its dynamic and adaptative perspectives, considering the human habitat, and enunciate SBE as a multidimensional approach through six ways of inhabiting: defensive, projective, scientific, thermodynamic, subjective, and complex. From these premises, to analyse the performance indicators that characterise these multidisciplinary ways of inhabiting, an IoT-driven methodology is proposed: to deploy a sensor infrastructure to acquire experimental measurements; analyse data to convert them into context-aware information; and make knowledge-based decisions. Thus, this work tackles the inefficiency and high energy consumption of public buildings with the challenge of balancing energy efficiency and user comfort in dynamic scenarios. As current systems lack real-time adaptability, this work integrates an IoT-driven approach to enhance energy management and reduce discrepancies between measured temperatures and normative thresholds. Following the energy efficiency directives, the obtained results contribute to the following: understanding the complexity of the SBE by analysing its thermal performance, quantifying the potential of energy saving, and estimating its economic impact. The derived conclusions show that IoT-driven solutions allow the generation of real-data-based models on which to enhance SBE knowledge, by increasing energy efficiency and guaranteeing user comfort while minimising environmental effects and economic impact.

Keywords: building thermal comfort; energy savings in buildings; hybrid twins; Internet of Things (IoT) ecosystems; knowledge-based decisions; smart built environment (SBE)

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1. Introduction

Buildings in the European Union (EU) are responsible for 40% of energy consumption and 36% of greenhouse gas emissions [1]. Non-residential buildings (institutions, industries, universities) contribute to around 20% of the total energy consumed. Given their savings potential, they have priority consideration in the EU 2030 agenda to meet the Sustainable Development Goals (SDGs) and commit to reducing energy consumption

+30% by 2030 [2]. In 2014–2020, the EU allocated EUR 14 billion to improve the energy efficiency of buildings [3]. The EU also budgeted EUR 5.4 billion in national co-financing for improving the Built Environment (BE), including public buildings (administrative, educational, sports, cultural, or institutional), private spaces (productive, commercial, or services), and infrastructure (travel and communication networks or green spaces). The EU estimates that 75% of the BE stock lacks efficiency and is +40 years old on average [4].

In Spain, buildings consume 1109 ExaJoules (EJ) of energy per year (1 EJ = 10^{18} Joules = 277.78 TeraWatts/hour), of which 54% corresponds to residential buildings, 35% to the tertiary sector, and 11% to the primary sector. The secondary energy consumed amounts to 3.103 EJ/year. Including energy losses due to conversions and system inefficiencies (1.347 EJ/year), the primary energy consumption in Spain reaches 4.45 EJ/year (compared to 581 EJ/year worldwide) [5]. For these reasons, energy efficiency is one of the EU's priorities for 2050, in line with the 1997 Kyoto Protocol [6] and the 2015 Paris Agreement [7].

Efficiency First [8] is the current motto of the energy policy that the EU has been legislating for over two decades through several directives: 2002/91/EC [9], 2010/31/EU [10], and 2012/27/EU [11] (in Spain RD 1826/2009 [12]). Recently on 8 May 2024, Directive 2024/1275/EU [13] established measures to enhance energy savings and efficiency in the BE using smart tools (Smart Efficiency, SE). This directive is complemented by several standards, including UNE-EN ISO 52120-1:2022 [14], which specifies the technical requirements and methodologies to meet legal and regulatory standards, UNE 178108:2017 [15], which promotes the integration of Internet of Things (IoT) technologies in building management, and UNE 178104:2017 [16], which advances efficiency and sustainability in smart cities by adopting new paradigms such as *hybrid twins*.

In this technological context, definitions of *smart* and *intelligent* (in buildings and architecture) since the 1980s [17] have stemmed from separate logics. In the initial definitions, a building (from an architectural approach) becomes smart through the addition of isolated elements designed for specific purposes (from a technological approach). These approaches, focused on buildings equipped with technology, remain very restrictive. To overcome this conceptual limitation and contribute to the understanding of what constitutes a smart building, this paper proposes extending the concept of intelligence to the entirety of the BE, avoiding the separation between environment and technology (buildings and spaces). In other words, it seeks to integrate the smart concept of BE by combining both architectural and technological approaches, thereby contributing to a holistic definition of the Smart Built Environment (SBE). Thus, this integrated contribution to the notion of SBE represents a comprehensive approach, over standard procedures, understanding the SBE as a complex system with the capacity to learn from empirical data in an interrelated way, generate transversal knowledge, and dynamically adapt its responses.

Based on these premises, this paper presents five key contributions: (a) conceptualising SBE by considering the human habitat from dynamic and adaptative perspectives (Section 3.1); (b) defining SBE as a multidimensional approach through six modes of inhabiting: defensive, projective, scientific, thermodynamic, subjective, and complex (Section 3.2); (c) integrating IoT ecosystems into the SBE as a proof-of-concept to obtain experimental measurements for analysing the SBE performance in alignment with energy efficiency directives (Section 3.3); (d) understanding the complexity of the SBE by analysing its thermal performance (Sections 4.1–4.4); and (e) quantifying the potential of energy savings based on thresholds recommended by the directives (Section 4.5) and estimating the associated economic costs (Section 4.6).

2. State of the Art Energy Efficiency and IoT in SBE

Energy efficiency and smart technologies have emerged as critical focus areas for reducing the environmental impact of the BE. In this context, IoT is key for revolutionising building management by enabling real-time monitoring, data-driven decision-making, and adaptive responses to climate change [18]. This section examines recent advances in energy efficiency and IoT applications in SBE, identifying gaps that this work addresses.

2.1. Advances in Energy Efficiency for Buildings

Efforts to enhance energy efficiency in the BE have globally intensified, driven by regulatory frameworks such as the Energy Performance of Buildings Directive (EPBD) [10]. This EU directive establishes benchmarks for reducing energy consumption, integrating renewable energy sources, and improving overall building performance. The promotion of Nearly Zero Energy Buildings (NZEBs) under the EPBD has catalysed advancements in passive design strategies, high-performance insulation materials, and energy-efficient Heating, Ventilation, and Air Conditioning (HVAC) systems.

Passive design strategies focus on using building orientation, natural ventilation, and daylighting to reduce reliance on mechanical systems. Recent studies demonstrate that integrating passive measures, such as double façades and advanced glazing systems, can enhance thermal performance and energy efficiency, especially in Mediterranean climates [19]. Similarly, the use of passive energy conservation strategies has shown significant potential for improving energy performance in residential buildings [20].

Innovations in HVAC systems, supported by smart control and IoT, are transforming energy efficiency in the BE. Recent studies highlight the effectiveness of using IoT technologies to optimise HVAC operations, achieving substantial energy savings, while maintaining thermal comfort [21]. Advanced differential pressure control mechanisms in HVAC systems further contribute to reducing energy consumption [22]. Retrofitting existing buildings with smart and energy-efficient technologies is a key strategy for reducing carbon footprints. An integrative review of retrofit strategies underscores the importance of combining passive and active strategies to achieve optimal energy performance [23]. Incorporating digital twin technologies into retrofitting projects has also shown promise for enhancing thermal comfort and operational efficiency [24]. Adaptive thermal comfort models, which consider behavioural and psychological adaptations to thermal environments, are key for energy efficiency. The adaptive comfort approach, emphasising flexibility in temperature setpoints, has been shown to significantly reduce energy use while maintaining occupant satisfaction [25]. This approach is particularly relevant in educational settings, as demonstrated in university buildings where thermal comfort is critical for user performance and well-being [26].

In summary, advances in passive design, adaptive models, efficient HVAC systems, and smart technologies contribute to enhancing building energy efficiency. But the successful implementation of these innovations relies on supportive policy frameworks, standardisation, and a comprehensive understanding of occupant behaviour and needs.

2.2. IoT Applications in SBE

IoT technologies have redefined building management systems by integrating sensors, actuators, and analytics platforms. These tools enable granular monitoring of environmental and operational parameters, leading to enhanced resource efficiency and user-centric management. IoT-enabled systems allow continuous tracking of temperature, humidity, occupancy, and energy use. For example, IoT-driven HVAC systems dynamically adjust their operation based on real-time conditions, achieving energy savings of up to 30% [21]. Similarly, smart lighting systems optimise energy use by adapting to occupancy and day-light availability [27]. In addition, IoT-driven predictive maintenance implies sensor data to detect anomalies and anticipate equipment failures. Recent studies have shown that integrating machine learning algorithms with IoT platforms can significantly reduce energy waste by ensuring timely interventions [22].

Also, IoT facilitates the integration of renewable energy systems into building management. By dynamically balancing supply and demand, IoT platforms optimise the use of on-site energy generation, such as solar photovoltaics, and reduce reliance on grid electricity [19]. Lastly, occupant behaviour plays a crucial role in energy efficiency. IoT technologies, within machine learning, enable personalised SBE by analysing user preferences and occupancy patterns. Such approaches not only enhance comfort but also optimise energy performance [27].

2.3. Challenges and Opportunities

Despite the transformative potential of IoT in SBEs, several challenges and opportunities persist in this researching scope. Data interoperability remains a significant hurdle, as heterogeneous devices and platforms often lack standardised communication protocols [24]. Furthermore, privacy and security concerns complicate the deployment of IoT solutions in sensitive environments. Nevertheless, emerging technologies, such as hybrid twin models that combine real-time IoT data with predictive simulations, offer innovative solutions. These models enhance decision-making by providing insights into complex behaviours of the SBE and enabling proactive management strategies.

This work builds on the existing literature by proposing a multidimensional framework for SBE that integrates IoT ecosystems with an in-depth understanding of the modes of inhabiting. Unlike previous studies (focused on technical or operational aspects), this work emphasises the interrelations between environmental, social, and cultural factors in shaping energy efficiency outcomes. By deploying a comprehensive IoT-driven methodology, this research contributes to the following: (1) enhancing data through sensor networks to collect and analyse contextual data, providing actionable insights for energy management; (2) user-centric design that incorporates user behaviour into decision-making processes to ensure thermal comfort while minimising energy use; and (3) policy integration, demonstrating compliance with international energy efficiency directives and offering evidence-based recommendations for further guidelines.

3. Materials and Methods

A holistic definition of SBE paradigm requires the understanding of the concept of *smart* as the ability to learn from empirical data, generate knowledge and rules, and adapt responses accordingly to that empirical data. This necessitates integrating capabilities to measure environmental and usage variables, standardise data, analyse it for decision-making, and implement decisions in management, regulation, and maintenance systems.

This knowledge must be processed to generate added value, transforming data into actionable insights that improve the overall performance and sustainability of the SBE. This initial definition should be complemented by various key topics grouped into four categories: digitalization (sensorization, measurement, technological infrastructure, data); management (cost-effectiveness, high performance, functionality, management, monitoring); environment (construction regulations, building quality, installations); and users (advanced societies, habitat, cultural context, social vulnerability) [28]. These diverse considerations highlight the multifaceted nature of the SBE and the need for a holistic approach to its development and implementation [29]. Therefore, the SBE paradigm should be extended to include several intelligences:

- Intelligent sustainable eco-design: Based on cultural and contextual criteria, including economic and ecological sustainability, smart architecture should strive for harmony with nature by responding to its physical laws and utilising its resources efficiently [30]. This approach emphasises that smart design extends beyond hardware and software to encompass broader contextual considerations, ensuring that the SBE contributes to a sustainable future;
- Intelligent contextual technology: Technology within SBE should be contextual and situated, combining existing technologies with the specific operating conditions of the SBE. Architecture relates its ways of building with its adaptability to the environment and its expression of cultural values. This context responds to a given boundary condition: the climatic situation, the available energy, the accessible materials, etc. This emphasises the need for technology to be integrated thoughtfully and respectfully within the SBE framework, intrinsically linked to how intelligence understands (within each culture) the relationship between building and environment, between living and being on Earth [31];
- Intelligent adaptive performance of buildings: The architectural configuration and utilisation of facilities should respond to the unique experiences of living in and with spaces in a specific location. Modern societies conduct most (work, personal, leisure) activities inside buildings. As current needs are dynamic and rapidly changing, buildings should adapt to these changes beyond simple maintenance or scheduling of services. This adaptability represents an inclusive form of intelligence, ensuring that SBE remains responsive to the evolving needs of its occupants [32];
- Intelligent inspiration and augmentation of occupants: The capacity to positively influence and maximise human creativity and intellect is crucial. As Winston Churchill stated, '*we shape our buildings; thereafter they shape us*'. Understanding the buildings should reflect a new relationship with nature. From this perspective, the SBE can intensify the relationship between inhabiting and environment. This can be performed by increasing knowledge of building behaviour through technology. This knowledge transcends a physical approach, encompassing how buildings respond to physical constraints, boundary conditions, and resource utilisation. It emerges from technology to empower creative solutions with intelligent capabilities and functionalities, influencing the well-being of people and the environment. This acquired knowledge should provide an intellectually enhanced understanding of the environment and the space we occupy, fostering a deeper connection between humans and the SBE [33].

All the above leads to the assertion that one of the defining characteristics of every smart building is its ability to adapt to singular conditions and dynamic evolution. To inhabit, unlike other objective and quantifiable processes, depends on multiple factors such as preferences, experiences, and culture of each inhabitant/user, among others. Moreover, these factors interact with systems, materials, and climate to form a complex system shaped by construction patterns [34]. To properly integrate these dynamics, it is essential to implement IoT strategies to provide two types of key information: IoT data (environmental variables and operating conditions of the SBE) and IoT feedback (user behaviour and its interaction with the environment). From this feedback perspective, the following Section 2.1 examines how the SBE, through IoT, can be understood as a dynamic habitat.

3.1. Dynamic Habitat

BE represents the way humans inhabit the world. Buildings are not merely a means, a tool, or an object, they can be considered an extension of the human being. This is the biological reason why people spend so much time in buildings; just as there is no ant without an anthill, termite without a mound, or bee without a hive, there is no human without a BE. Buildings are an intrinsic part of how we exist. Beyond reasons of comfort, well-being, or convenience, buildings are the means through which humans adapt to and shape their environment: '*we are, if nothing else, builders, and that leads us to admire other builders*' [35]. This adaptation to the environment refers to an organism's ability to adjust to the demands and challenges of its habitat, which is full of changing situations. In other words, it is the capacity to solve problems effectively in open and uncertain environments. Unlike automated systems, which operate in controlled settings, the human habitat is filled with unstructured information and uncertainty [36]. In this context, the concept of bounded rationality [37] is developed to explore how systems (both automated and biological) make decisions under conditions of incomplete information, unpredictable changes, and complex environments. Therefore, from this perspective, an effective definition of intelligence requires studying how biological systems operate.

In turn, intelligence emerges from direct interaction with the environment, according to the principle of strict reliance on interfacing to the real world through perception and action [38]. This gives rise to the concept of *situated knowledge*, where the notion of intelligence arises from continuous interaction with complex and dynamic environments without relying on a static representation. For the system, an exhaustive representation of the world is not necessary. This emphasis on behaviour within an environment, independent of the autonomous system's design, is demonstrated through real-time actions [38]. We also find this adaptability or contextuality in the theory of intelligence, where intelligence is defined as the ability to adjust to new and unknown situations within a given environment. In addition to adaptation, it is essential to draw on prior experience to solve problems in a specific context, where the abilities to analyse, evaluate, judge, and compare are as necessary as the capacity to generate new ideas in response to unexpected situations.

For the authors previously cited [30–38], intelligence is demonstrated as a dynamic adaptation to the environment, enabling organisms to successfully respond to opportunities in their surroundings. For instance, various studies seek to understand how biological systems interact to apply these principles to human intelligent systems. Some even focus on how the brain functions to use sensory information to predict the next state of the world. They suggest that the brain makes predictions based on previously learned patterns, and that this predictive ability is fundamental to intelligence.

From these approaches, the concept of intelligence has traditionally been linked to self-awareness and a complete representation of the world. In this view, decision-making in uncertain environments (where mobility is a key factor for humans) requires highly comprehensive information to create an operational representation. Initially, compared to other complex artificial systems (such as autonomous driving) the BE may appear highly static and passive; and yet, it is not. To illustrate this, it is helpful to analyse the intelligence of plants where decisive factors include individual consciousness, environment representation, and mobility [39]. In this context, buildings share similarities with plant systems; they are closely tied to a specific location, must adapt to highly specific and localised environmental conditions, and their construction and operation transform the land on which they stand. The cumulative impact of their emissions can alter atmospheric composition, they require water supply and waste management, they interconnect with one another to form a complex system (a city), and they can harness solar energy through photovoltaic systems. Therefore, understanding how intelligent adaptation to the environment occurs in the plant world can be highly relevant for defining the concept of the SBE.

Studies on plant intelligence [40–44] suggest that the intelligent adaptive capacity of plants to optimise their growth conditions relies on gathering information about their environment through their sensory capabilities. In terms of the SBE, this concept is comparable to IoT ecosystems. Research has shown that plants can receive stimuli from their surroundings through specialised structures, enabling them to detect and respond to changes in their environment without relying on a central control organ [40]. It has been proven that trees have sensory cells that allow them to detect soil moisture, light intensity, and ambient temperature. Additionally, they can sense the presence of herbivores and certain pathogens, responding to them by producing specific chemical compounds [41]. They exhibit growth patterns influenced by gravity, the location of minerals, water composition, the presence of other species, wind, and more. They even emit chemical and electrical signals to communicate with one another, exchanging information. Following these premises, an intelligent system would not rely on its capacity for consciousness or mobility but rather on its ability to make decisions in an environment of uncertainty. As demonstrated with plant systems, buildings can become intelligent by incorporating systems to capture environmental signals, process information, and respond with more adaptive (and therefore intelligent) behaviour [42]. Additionally, plants (as well as ants and bees) exhibit characteristics of distributed intelligence [43], which challenges the notion of intelligence as an individual property. From these approaches, the definition of the SBE should be expanded to include complex and highly collaborative behaviours as models of distributed intelligence, where multiple nodes (agents) operate autonomously or in a decentralised manner to achieve a common goal. Biologically inspired algorithms, such as *swarm intelligence* [44], are based on the idea that each node (agent) processes and responds to the environment independently while contributing to the overall system behaviour.

As plants, an SBE should gather environmental data (through IoT), process and analyse it, and make decisions (in a collaborative and interconnected way) toward a goal. Defining a specific goal is crucial to understanding how a system solves complex problems, moving it closer to that goal, even under changing and complex conditions. In biological systems, these goals are typically related to survival and reproduction. In artificial systems, the goals must be defined to guide adaptive decisions. However, in the SBE, defining goals presents challenges. Beyond survival, human-built environments also encompass ethical, aesthetic, political, cultural, economic, energy-related, and technical values. Figure 1 shows a visual representation of habitat evolution that elucidates the notion of SBE as a complex and multifaceted system, underscoring the necessity of a holistic approach to building design and maintenance. This holistic approach, when all these purposes are intertwined, becomes challenging to clearly establish a primary (and measurable) goal for the SBE. While some studies are beginning to consider social and cultural aspects in the design of smart buildings, most research tends to prioritise operational efficiency and sustainability without addressing other objectives. These overlooked objectives often play a significant role in shaping architectural decisions and heavily influence their engineering. Thus, to enunciate a holistic definition of SBE, Section 3.2 proposes a multidimensional approach to dynamic habitat contributing to six ways of inhabiting: defensive, projective, scientific, thermodynamic, subjective, and complex.

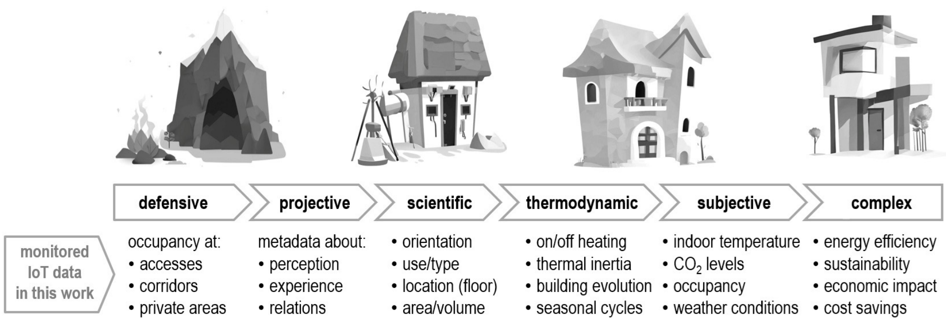


Figure 1. Modes of inhabiting. Evolution and relationship with monitored IoT data in this work. AI-generated images by pixlr.com (accessed on 20 December 2024).

3.2. Modes of Inhabiting

As previously mentioned, defining a single purpose for the SBE is challenging. To address this issue, it is essential to study the processes related to human inhabitation and its evolution. By analysing this evolution, it becomes possible to understand the significant adaptation of the BE to major changes and pressures from their surroundings. This adaptation has enabled the development of diverse configurations, the ability to respond to complexity, and the capacity to provide greater well-being. From this point, the challenge of a complex system lies in evaluating its internal functions, which requires selecting an appropriate set of indicators. Animal construction systems have always addressed key requirements such as protection from climate, predators, and competitors as determining factors. However, human systems go far beyond this, serving as manifestations of cultural values, thought systems, and social principles [45].

In this sense, different modes of inhabiting can be described as outcomes of several BEs designed for specific cultural, technological, and social contexts. These modes are defined with the understanding that these contexts overlap; meaning that, while a simplified definition might be necessary, multiple modes of inhabiting coexist. Therefore, for an SBE proposal to respond to a broad and multidimensional context (and not merely its protective needs), it is essential to determine which mode of inhabiting is predominant. Failing to do so risks creating SBEs that respond only (and narrowly) to specific building purposes (such as energy consumption), while neglecting key perspectives (such as maximising interactions and fostering relationships to build a sense of belonging and identity).

This is particularly relevant in university buildings designed for a community of researchers, local entrepreneurs, and young students. From this perspective, this paper proposes in a novel way that, when defining the objectives and purposes of an SBE, it is essential to clarify which mode of inhabiting is being addressed. This presents a challenge, as the objectives will vary in each case; therefore, so will the means to achieve them. Thus, before implementing an SBE, it is necessary to define its modes of inhabiting and determine which type of context each one responds to. These definitions are proposed as open-ended, encouraging a reflective process of identification and evolution. Furthermore, this proposal represents a conscious approach that architecture (answering to societal dynamics) can encompass multiple modes of inhabiting. However, these modes are neither homogeneous nor neutral but rather complex and interconnected. From all these premises, and based on cultural, social, ethical, technical, and economic values, this paper contributes to defining the SBE through six modes of inhabiting (see Figure 1 and Table 1).

- Defensive. Buildings are often understood as shelters from a hostile world. Humans perceive themselves as part of that world. This mode of inhabitation aligns with the laws, norms, and patterns that humans can deduct from natural phenomena. The objectives of this mode are related to safety (structural, intrusion, etc.); thus, this work has monitored occupancy data (including access doors, corridors, private areas, etc.);
- Projective. One of the defining characteristics of humans is their ability to imagine what might happen and to invent reasons, myths, or question whether there is more to reality than what is perceived through the senses. Metaphysics, mythology, and religion suggest that existence on Earth has a purpose, a journey, or transcendence. Inhabiting the Earth is seen as temporary, a step in a process of transition and transformation. Humans build temples and monuments with meaning and purpose that transcend their mere functions or materials. The objectives of this mode are related to aesthetics, scale, and illumination; thus, this work has included metadata about comfort perception, user experience, and subjective relationship with spaces;
- Scientific. Scientific thought enables the calculation and prediction of the outcome of an action/process before it occurs. It relies on a reductionist analysis of parts to

understand the whole. This reductionist establishes a division between body and mind. The world becomes a means to an end (abstract thought), making it possible to adapt any space to serve thought. Understanding the laws of nature allows for a mode of inhabiting "outside" of nature. The BE becomes a temporary passage for the mind. But now the mind is also a command centre for the body, from which to extend control over nature and extrapolate this dominion to the rest of the universe. The Cartesian concept also introduces the idea of isotropic and homogeneous space, enabling the understanding of territory as a limitless map for deploying thought. The objectives of this mode are related to rationality, order, circulation, proportion, and composition: thus, this work has categorised architectural spaces into zones (orientation, use, floor, etc.) and quantified different key parameters (area, volume, location, etc.);

- Thermodynamic. There are limits, processes are finite. Machines are built, composite materials are manufactured, and objects are moved but everything has a limit. Fossilised plant energy stored over aeons can be processed, and any space can be thermally conditioned regardless of external or local conditions. In other words, the act of inhabiting can be made thermally comfortable through energy (which is limited). Thus, the combination of an outdoor homogeneous space and the ability to make any indoor space habitable dissolves the notion of adapting to the environment, as the environment is instead adapted to the human being. Governed by energy consumption, this thermodynamic mode emphasises comfort and efficiency; thus, its objectives are related to energy consumption: so, this work has included monitoring of key parameters such as heating on/off times, building thermal inertia, building temperature, and its evolution in the architectural structure according to seasonal cycles;
- Subjective. A third interior habitation space emerges: subjectivity. This is an introspective perspective focused on building and inhabiting a strong sense of self. For this self, limits such as ageing and death remain, but advances in medicine improve living conditions regardless of where or how one inhabits. The identification of external pathogens capable of threatening the self-places emphasis on strengthening the immune system through isolation and hygiene. Consequently, inhabiting becomes homogeneous, enclosed, and hygienic, reinforcing separation from the outdoor. In other words, if any home can be adapted to thermally comfortable conditions and health can be improved through medication, this subjective mode (as a way of being in the world) becomes relative. Inhabiting (and therefore architecture) follows the criteria of subjectivity (influenced by fashion, opinion, or taste), with a focus shifting predominantly to the visual and aesthetic. The capacity of architecture to influence behaviour or provide protection becomes irrelevant. Thus, the objectives of this mode are related to isolation, filtering, control, regulation, and airtightness; so, the proposed methodology incorporates monitored data from several approaches: indoor temperature, CO_2 levels, occupancy, and building temperature (from the built environment); outdoor temperature and meteorological conditions (from weather scope); and comfort, energy cost, and economic impact (from a user perspective);
- Complex. From individual boundaries, it becomes evident that humans are not isolated; every action affects both the individual and others. Every action has its reaction. This is a feedback-driven, interconnected reality (non-Newtonian) where concepts like cause and chance are replaced by patterns and uncertainties. In other words, reality is composed of patterns (not universal laws) that, in turn, depend on our ability to observe the world. Possibilities exist, not certainties. We belong to a network (life) filled with interconnections and interdependencies: between us and others, between the environment we inhabit and how we inhabit it. We adapt the environment to ourselves while simultaneously adapting ourselves to the environment

in a feedback loop. Therefore, all habitation is identity, interconnection, and feedback, making it inherently a complex system. The objectives of this mode are related to interconnection (knowing when to open or close) and relationship (quantitative and qualitative) with the environment; thus, the proposed methodology correlates monitored data from several perspectives and, with specific results of this work, contributes with an economic quantification to show the savings potential.

Table 1. Modes of inhabiting. Systematic overview and key objectives.

Mode	Description	Key Objectives
Defensive	Buildings as shelters from a hostile world, focusing on safety (structural, fire, intrusion).	Safety (structural, fire, intrusion)
Projective	Human imagination and transcendence, creating structures with aesthetic and symbolic purposes (e.g., temples, monuments).	Aesthetics, scale, illumination
Scientific	Rational analysis and prediction, with objectives of rationality, order, and control over nature.	Rationality, order, circulation, proportion, composition
Thermodynamic	Focus on thermal comfort and efficiency through energy consumption, adapting the environment to humans.	Energy consumption, comfort, efficiency
Subjective	Isolation and hygiene to protect the self, with emphasis on aesthetic and visual appeal in architecture.	Isolation, filtering, control, regulation, airtightness
Complex	Interconnected systems adapting to and influencing the environment, emphasising feedback and identity.	Interconnection, relationship, feedback

The various ways humans conceptualise (even themselves) imply different modes of inhabitation. Conversely, each mode of inhabiting is a response to a way of thinking about the world. As mentioned, all these modes coexist; we navigate through all of them. Furthermore, all these modes coexist within each individual. The defensive mode can by no means be considered obsolete, as we are living beings and still need to survive within our environment. As humans, the imagination of the projective mode allows us to access what does not yet exist and, therefore, to invent, dream, and project utopias. The scientific mode serves as the theoretical foundation of classical reductionist education. The thermodynamic mode provides the exosomatic energy that underpins civilization. The subjective mode (self-centred) focuses on constructing identity and an ego that defends and protects itself. The complex mode is evident in our daily transcultural, technological, and interconnected lives. Moreover, the recent pandemic, energy, and environmental crises will shape and redefine the modes of inhabitation in the future [46]. Based on this complex and interconnected reality, it is essential to implement IoT strategies to collect data that can be used to analyse the behavioural parameters characterising these modes of inhabiting. Thus, Section 3.3 proposes an IoT-driven methodology to identify buildings, select ubications, deploy a sensor infrastructure, acquire experimental measurements and context-aware information, and analyse the obtained results, as discussed in Section 4.

3.3. IoT-Driven Methodology

This work follows an IoT-driven methodology, as shown in Figure 2a, supported by previous knowledge and work [47,48]. The methodology steps are as follows:

1. Identification of buildings, regarding several key performances: orientation (north, south, east, and west), thermal variations, use of patterns (schedules, timetables), etc. Figure 2b shows smart campus, representative for extrapolating other SBE;
2. Selection of ubications, see Figure 2c, following several key characteristics: location (floor, sector, building, campus), use (classroom, study room, office, laboratory, etc.), size (large, medium, small), occupancy (high, medium, low), among others.
3. Deployment of sensor infrastructure. The IoT ecosystem of this work includes +200 geolocated wireless sensors that collect +1000 real-time measurements every hour. Figure 2d illustrates sensor examples with the following characteristics and metrics:

- VS121 www.milesight.com/iot/product/lorawan-sensor/vs121 (accessed on 20 December 2024): occupancy smart sensor for anonymous people counting data to monitor and understand space utilisation;
- AM307 www.milesight.com/iot/product/lorawan-sensor/am319 (accessed on 20 December 2024): Indoor Air Quality (IAQ) sensors to detect CO_2 concentration, temperature, humidity, light, HCOH/O3 levels, TVOC, atmospheric pressure, PM 2.5, PM10 and motion;
- QPA1004 mall.industry.siemens.com/mall/es/es/Catalog/Product/S55720-S453 (accessed on 20 December 2024): room air quality sensor to detect CO_2 concentration, temperature and humidity;
- EM500 www.milesight.com/iot/product/lorawan-sensor/em500-pt100 (accessed on 20 December 2024): industrial temperature equipment equipped with a high-precision PT100 sensor;
- Khomp Meteo www.khomp.com/iot/en/produto/endpoint-lora-station-meteorological (accessed on 20 December 2024), meteorological station that combine 7 sensors to capture temperature, humidity, rain, wind speed and direction, ultraviolet radiation and atmospheric pressure;

4. Acquisition of experimental measurements. The key IoT variables monitored in this work are as follows: temperature (indoor, building and outdoor), CO_2, occupancy, humidity, light level, among others. This set is added to more external variables (to obtain SBE context-aware information) such as lecture schedule, weather conditions, architectural norms, heating on/off times, thermal thresholds, energy cost, among others;
5. Analysis of results. This step enables multidisciplinary studies; this work, within international directives about smart energy efficiency, follows the current legislation:

- RDL 486/1997 [49], which states that 'indoor temperature in spaces where sedentary work typical of offices or similar activities is performed must be between 17 and 27 °C'. Thus, the minimum threshold is set at 17 °C; below 17 °C, it is mandatory to turn on the heating;
- RDL 14/2022 [50], which states that 'the indoor temperature in heated spaces must not exceed 21 °C when conventional energy is required to generate heat through the heating system . . . the scope of application includes buildings for administrative use . . . and universities)'. Thus, the maximum threshold is set at 21 °C; above 21 °C, it is advisable to turn off the heating to promote energy savings;
- EN 16798-1:2019 [51], which states various tolerance ranges to fulfil adaptive thermal comfort, stating that 'the indoor temperature should round 19° C'. Thus, the thermal comfort threshold is set at 19 °C by analysing ranges between 17 and 19 °C and 19 and 21 °C.

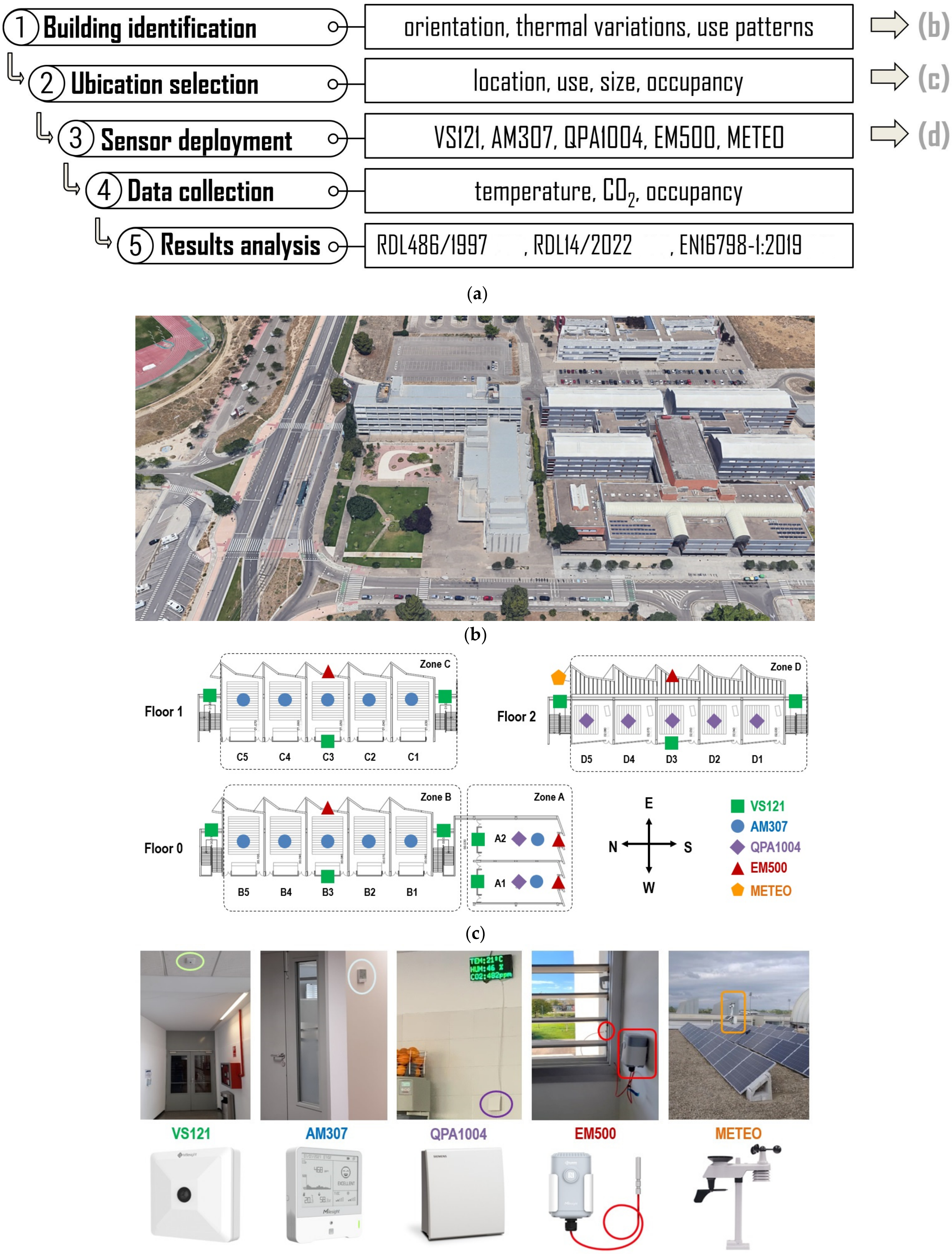


Figure 2. IoT ecosystem deployed in smart campus: (**a**) Methodology steps [49–51]; (**b**) Campus and buildings; (**c**) Labelled ubications; (**d**) Examples of geolocated infrastructure with detail of sensors.

4. Results

From the proposed methodology, the obtained measurements are presented. This work has studied IoT data during the autumn-winter period (October, November, December 2023, January and February 2024) to propose two contributions: (a) understanding the complexity of the SBE by analysing its thermal performance (Sections 4.1–4.4); and (b) quantifying the potential of energy savings, following the thresholds recommended by the directives (Section 4.5) and estimating its economic costs (Section 4.6).

4.1. Analysis of Thermal Evolution

To begin the analysis, a general comparison of temperature trends is presented. Figure 3 shows the average temperature, calculated as the mean of the indoor temperatures in each monitored space (weekly and monthly), offering the following interesting insights:

- October temperatures (solid blue curve) exceed 21 °C. This can be attributed to good weather conditions during this month (solid black line) [52], which can be quantified as an average thermal inertia of approximately 2–3 °C above outdoor temperatures;
- With these favourable temperatures, heating is not activated. Subsequently, Section 4.3 compares October (without heating) with the other months (with heating) to analyse the climate behaviour of the building. Furthermore, October (without heating) is chosen in Section 4.4 to analyse the behaviour (net, without heating influence) of indoor temperatures, their evolution, and their morphological characteristics;
- During the other months with heating (red, green, and yellow curves), compared to October without heating (blue curve), the behaviour is more uniform remaining within an approximate range of 6 °C (between 17 °C and 23 °C, the thresholds are marked by the dashed black lines). Additionally, in all cases, each day of the week follows a rise-and-fall pattern, which, weekly, defines a sawtooth behaviour. To understand this phenomenon, is key to study the thermal inertia of the building, see Section 4.2;
- During the months with heating, the drops in average temperatures reveal periods where heating is off. As outlined in black boxes (and analysed in detail in Section 4.2), these correspond to holidays periods (green curve), specifically in week 1 (6–8 December) and week 4 (23–31 December);
- Detailing months with heating, the average temperatures in November (red curve) are higher (by 1–2 °C) compared to December and January (green and yellow curves). As discussed in Section 4.2, this is due to better weather conditions in November;
- Several behaviours related to occupancy stand out (as analysed in Section 4.4). Week 1 of January (yellow curve), shows lower temperatures. This week is non-teaching but still a working period; thus, even though the heating is on, the thermal inertia must recover after many days without heating (since week 4 of December, green curve). This requires the entire week 1 in January to reach the average temperature range of the other months (from 17 °C). Additionally, January (yellow curve) shows the greatest variation between maximum and minimum temperatures. In this campus context, this is explained by the non-teaching period (exams season), which results in lower average occupancy and, consequently, daily temperature drops to lower minimums.

These trends highlight that the proposed IoT-driven methodology, based on real-time monitoring of experimental measurements, pursues a double contribution:

- to compare measurements of the current year with previous years to make experience-based decisions. In Mediterranean climates, the fall season usually alternates cold-dry with warm-wet periods; thus, the results of this work will serve as behaviour patterns on which to adjust pattern-based prediction models;

- to include new measurements (from season to season) into the IoT datasets to incorporate this knowledge into the prediction models and retraining them iteratively to obtain predictions adjusted to climate reality.

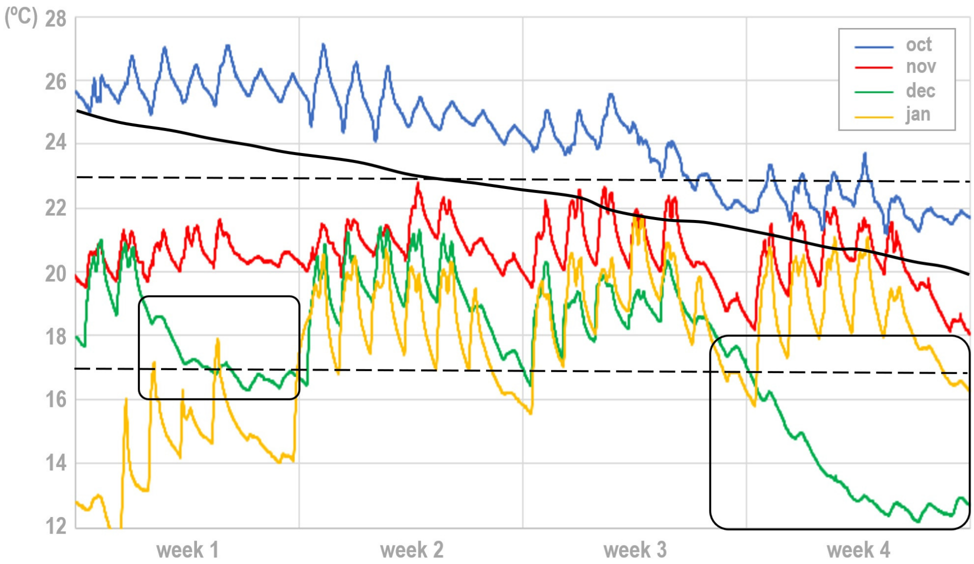


Figure 3. Analysis of thermal evolution in the autumn–winter period.

4.2. Analysis of Thermal Inertia

To advance the study, the thermal inertia of the building is analysed, specifically, how the building retains heat over the course of consecutive days within the same week. For this purpose, the daily temperature trends are monitored for the 4 weeks across the 4 months with heating on. Figure 4 illustrates the evolution of the average temperatures of the building façade (orange curve) compared to the weather conditions (blue curve), highlighting the following observations:

- In November, the weekday temperatures (Monday to Friday) for all weeks show a pattern similar to the evolution of the weather conditions. Over the weekends, the average temperature (orange curve) drops, due to the absence of occupancy and the heating being turned off;
- In December and January, the Christmas holidays are highlighted with green boxes in Figure 4b,c. Additionally, as shown in Figure 3, there are marked drops in temperatures (orange curve);
- During week 2 of December, when the weather follows a progressive cooling trend (blue curve), the heating gradually increases the temperatures (orange curve). The predicted effect occurs (black arrows), where the temperatures toward the end of the week surpass those of earlier days due to the thermal inertia. This effect is also observed in week 3, especially in the evolution of minimum temperatures;
- Following this explanation, the sawtooth pattern of progressively rising temperatures as the week progresses is more noticeable when the weather also follows an upward trend, as seen in weeks 3 and 4 of January (black arrows);
- In February, this effect is also observed (black arrows), leading to the conclusion that regardless of weather conditions, heating causes a progressive rise in temperatures (Monday to Friday and cumulatively over the 4 weeks of the month), defined by a sawtooth pattern.

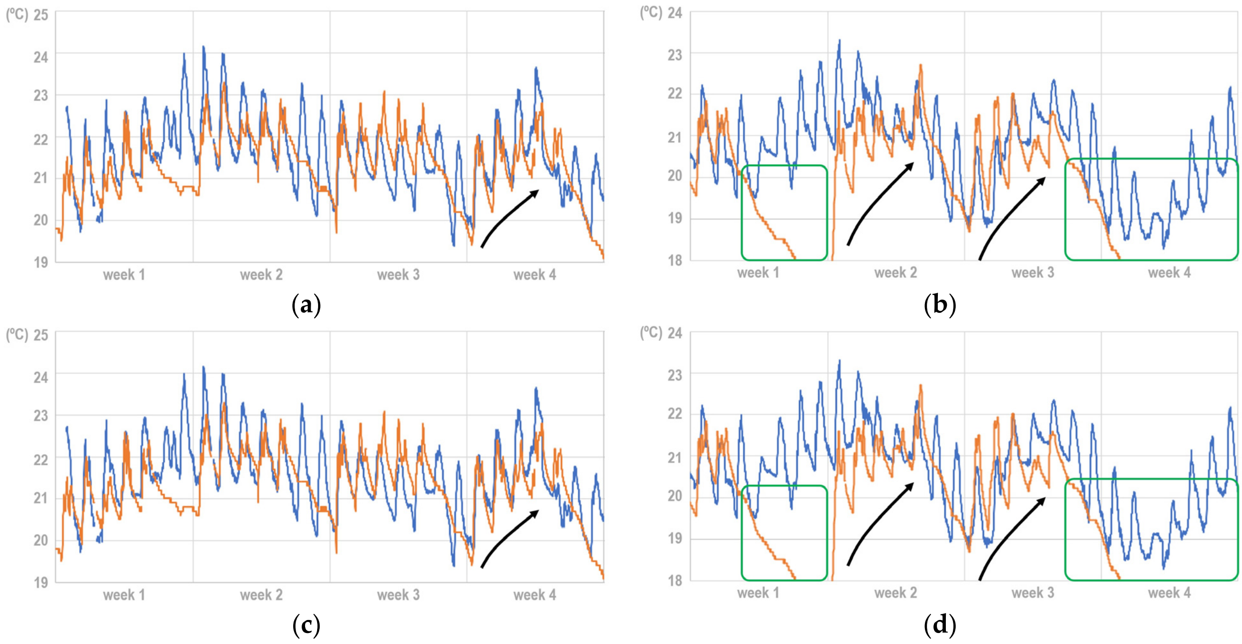


Figure 4. Analysis of thermal inertia: (**a**) November; (**b**) December; (**c**) January; (**d**) February.

To deeper analyse the thermal inertia, the temperature trends are examined during two holiday periods and highlighted as black boxes in Figure 3: period 1 (6–10 December, see Figure 5) and period 2 (23–31 December, see Figure 6). Figure 5a illustrates the weather conditions, showing maximum temperatures ranging between 10 and 14 °C (first three days: 6th, 7th, and 8th), followed by an increase to 18 and 19 °C (on the 9th and 10th days). Figure 5b compares the average temperatures across several zones, following the layout in Figure 2b. Zones A, B, and C (yellow, green, and blue curves) display similar trends, while Zone D (red curve) records the lowest temperatures (with the largest variations). This is explained because Zone D (top floor) is more exposed to weather conditions. Additionally, as it is winter and spaces remain unoccupied during the holidays, Zone D is more affected by low temperatures. Comparing Zone D temperatures, see red curve in Figure 5b, with weather conditions, see Figure 5a, a similar pattern emerges, allowing to quantify a thermal inertia of approximately 3 °C above the outdoor temperatures.

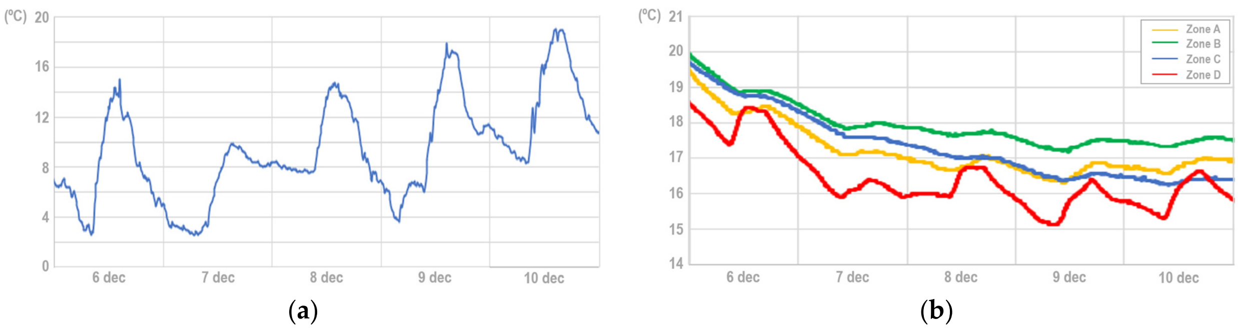


Figure 5. Analysis of thermal inertia (holyday period 1): (**a**) Weather; (**b**) Comparison by zones.

Similarly for holiday period 2, Figure 6a shows a gradual decrease in temperatures (from the 23rd to the 28th days) by approximately 16 °C, followed by a rise (from the 28th to the 31st), returning to the original 16 °C. Figure 6a again confirms that Zone D records the lowest temperatures, as previously explained, due to its exposure to weather conditions. Observing the first five days (23–28) and comparing Figure 6a,b, a thermal inertia of approximately 3 °C above the outdoor temperatures is again confirmed.

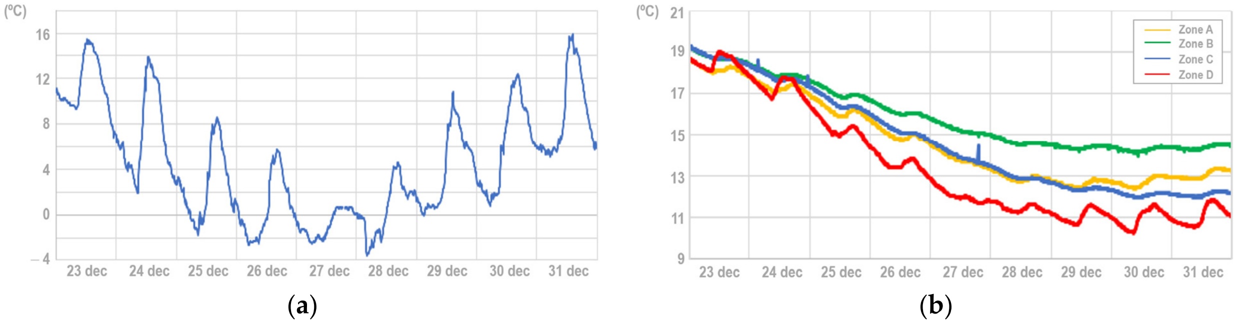


Figure 6. Analysis of thermal inertia (holyday period 2): (**a**) Weather; (**b**) Comparison by zones.

4.3. Analysis of Heating Influence

After thermal inertia, further analysis examined the heating influence on the thermal behaviour, by comparing the temperatures evolution between October (without heating) and November (with heating). Figure 7 shows the average temperatures for October (blue curve) and November (red curve), highlighting the following observations:

- In October (blue curve), the building temperatures proportionally decrease with the weather pattern (dashed blue curve), as analysed in Section 4.1. However, in November, the building remains within a uniform range between 19.5 and 22.5 °C (dashed red lines) because of heating. Furthermore, as discussed in Section 4.6, this range complies with recommended directives: in winter, indoor temperatures should be between 17 °C and 21 °C, considering thermal comfort to temperatures around 19 °C;
- In November (red curve), as indicated in Section 4.2, heating results in a uniform rise-and-fall pattern throughout a week. In October (blue curve), this pattern is less recognisable because weather conditions become the dominant influencing factor. This leads to an analysis of morphology of thermal behaviour, detailed in Section 4.4.

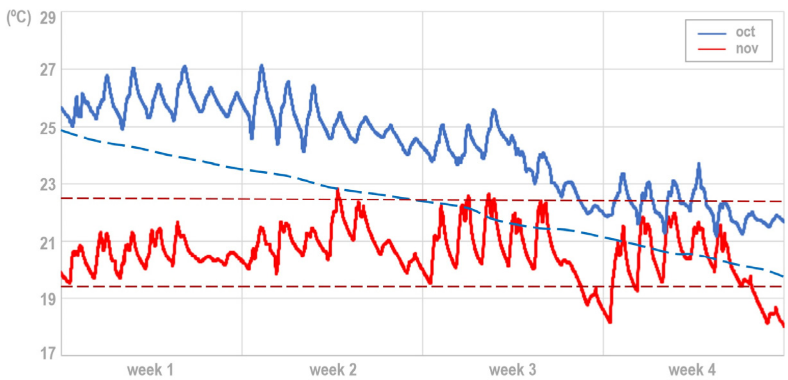


Figure 7. Analysis of heating influence.

To further analyse the uniform pattern with heating, Figure 8a shows the detailed temperature evolution for November (red curve), including the timeslots when the heating is on (orange vertical stripes). These timeslots (on/off switching) follow criteria from Green Office [53], according to a threshold algorithm (by comparing the weather in previous days), and fulfilling the mentioned directives RD 486/1997 [49], RDL 14/2022 [50], and EN 16798-1:2019 [51]. As Figure 8a shows, temperatures remain within a uniform range (green lines), which varies by week: between 20 and 22 °C (weeks 1 and 4), 21.5 and 23 °C (week 2), and 21 and 22.5 °C (week 3). This demonstrates that the heating effectively regulates and stabilises temperatures, maintaining consistency from day to day, even when weather conditions vary. Figure 8b, adding outdoor temperatures (blue curve) to Figure 8a, shows that indoor temperatures remain uniform although weather conditions fluctuate. Note that the outdoor temperatures (blue curve) are decreasing (in week 2 and 3) while heating maintains the indoor temperatures (red curve) within a uniform range (green lines).

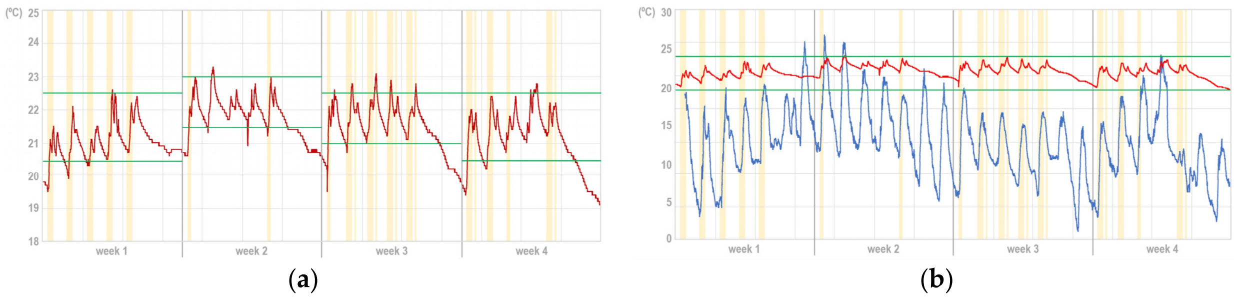


Figure 8. Analysis (detailed) of the heating influence: (**a**) Thermal evolution vs. heating; (**b**) Thermal evolution vs. heating vs. outdoor temperature.

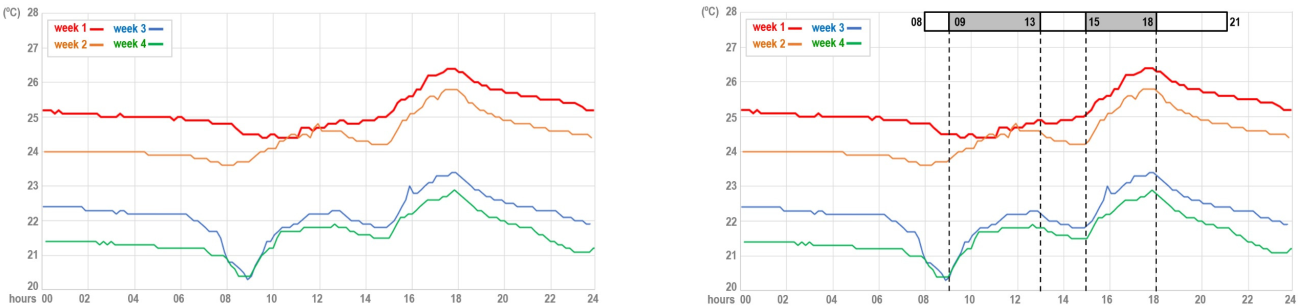
4.4. Analysis of Thermal Morphology

From the uniform pattern when the heating is on, this section analyses the thermal behaviour without heating. This led to an analysis of the morphology of temperature evolution. As an initial approach, the thermal behaviour is compared with itself on the same day of the week during a month. Based on a review of university lecture schedules, Tuesday has been identified as the most representative day for this study. Figure 9a shows the temperature evolution (from 00:00 to 24:00 h on the X-axis) over the four weeks of October: red (week 1, Tuesday 3rd); orange (week 2, Tuesday 17th, as 10th was a holiday); blue (week 3, Tuesday 24th); and green (week 4, Tuesday, 31st). Although no general pattern emerges, several areas of temperature increase and decrease can be identified. To explain these trends, Figure 9b builds upon Figure 9a by adding vertical black lines following occupancy schedules (obtained from [54]). A horizontal band (at the top) indicates the building's opening hours (from 8 h to 21 h), while occupied hours are highlighted in grey. This study contributes to the conceptualisation of a morphological pattern, divided into following several key areas, as illustrated in Figure 9b:

- Initial linear behaviour before the first grey band (start of classes at 9 h);
- Upward behaviour during grey bands (lectures schedule), due to occupancy;
- Downward behaviour after the last grey band (end of classes at 18 h), that stabilises at a level similar to the initial linear behaviour and start of the curve for the following day. The difference between initial and final daily temperatures is modulated by the average building temperature, which is conditioned by the weather conditions, as discussed in Sections 4.2 and 4.3;
- Downward behaviour between grey bands (can be multiple on a day regarding schedule), related to absence of people. This will be discussed in Section 4.6 by including the relationship with other key variables, as evolution of CO_2 levels;
- Several non-pattern behaviours (as downward level at the beginning of the day, previous of first classes), related to unpredictable situations: opening of windows or doors, presence of people out of their schedule, etc. This confirms the interest of understanding the complexity of the SBE, as contributed by this work.

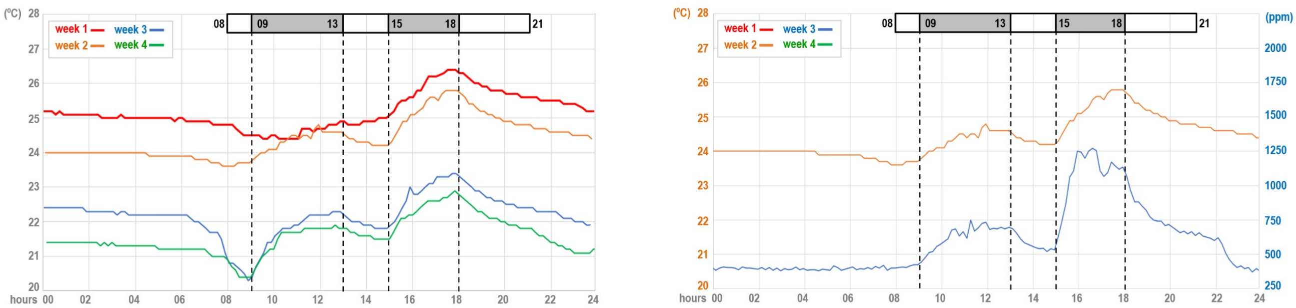
To complete this morphology study, the comparative thermal evolution is analysed along with their interrelationship with other study variables, such as CO_2 and occupancy. For example, Figure 10b shows the temperature in week 2, orange line extracted from Figure 10a, compared with the evolution of CO_2 (blue line, scaled in right Y-axis). The thermal increases-and-decreases can be explained following the rise-and-fall of CO_2 levels (blue line). Furthermore, these thermal increases-and-decreases and rise-and-fall of CO_2

levels coincide with grey bands of occupancy. This confirms that, with occupancy (from 9 h to 13 h and 15 h to 18 h), shaded in yellow in Table 2, the temperature increases (orange line) and CO_2 rises (blue line). This led to the use of IoT ecosystem to confirm the expected occupancy and to explore an interesting featured application as a detector of anomalous situations. An example of this potential use is shown in the temperature evolution of week 1, see the red curve in Figure 10a. Between 9 h and 13 h (where an increase would be expected) the temperatures remain linear. However, upon checking the timetable, see Table 2, it confirmed that classes from 9 h to 13 h had not yet started during that first week, meaning the space was empty. This demonstrates the absence of people, which justifies those temperatures remain linear.



(**a**) (**b**)

Figure 9. Analysis of thermal morphology: (**a**) Daily evolution; (**b**) Daily evolution vs. occupancy.



(**a**) (**b**)

Figure 10. Analysis of thermal morphology. Comparison with CO_2 levels and occupancy: (**a**) Daily evolution vs. occupancy; (**b**) Daily evolution vs. occupancy vs. CO_2 levels.

Table 2. Detail of daily occupancy. Source: https://reservadeaulas.unizar.es (accessed on 20 December 2024).

Day	08–09	09–10	10–11	11–12	12–13	13–14	14–15	15–16	16–17	17–18	18–19	19–20	20–21
Oct. 03								class	class	class			
Oct. 17		class	class	class	class			class	class	class			
Oct. 24		class	class	class	class			class	class	class			
Oct. 31		class	class	class	class			class	class	class			

Abnormalities in the relationship between indoor temperature and occupancy arise due to two main factors: technical and human. Technically, the algorithms to count people that include occupancy sensors are still inaccurate. This work complements occupancy data with academic calendar and timetable schedule but class attendance is not mandatory and sporadic uses of classrooms are not reflected in the reservation schedules, then unpredictable increases in temperature appear. Thus, CO_2 levels are used as an additional indicator, and ongoing research aims to improve occupancy estimates by combining CO_2 and presence sensors. The other human factor is about periods when classrooms are open, such as cleaning (between 6 h and 7 h 30), breaks (between classes), ventilation (when windows or doors are opened by teachers or students), or lighting (blinds are adjusted to improve lighting or reduce glare). These temperature-occupancy discrepancies reduce quickly the indoor temperature even when occupancy is high.

4.5. Analysis of Potential Energy Savings

Previous results (Sections 4.1–4.4) provide insights into the thermal behaviour. Based on these findings, Section 4.5 aims to quantify the potential energy savings according to the recommended thresholds of 17, 19, and 21 °C (as presented in the Introduction). Thus, temperature measurements have been quantified at each monitored space, see Figure 2b, during the building's opening hours in the timeslots when the heating is on (for each month with heating: November, December, January, and February). Table 3 shows the time percentage that temperatures met in each one of the following ranges:

- Below 17 °C: range when heating should be turned on to achieve thermal comfort. Ideally, percentages should be close to 0%;
- Between 17 and 19 °C: range following EN 16798-1:2019 [51]. Due to comfort sensation rounds 19 °C, this is a restrictive threshold (for energy saving) that, ideally, should be around 50%;
- Between 19 and 21 °C: range of thermal comfort that, ideally, should be around 50%:
- Between 17 and 21 °C: range following directives RD 486/1997 [49] and RDL 14/2022 [50]. As addition of two previous ranges (17–19 °C and 19–21 °C), ideally should be 100%;
- Above 21 °C: range when heating should be turned off. Percentages above 0% mean potential energy savings, as be quantified and discussed in next Section 4.6.

From these premises, monthly results are analysed (see Table 3):

- November shows good weather conditions (average of 9.8 °C). Thus, only D4 and D5 (blue background) remain below 17 °C for less than 5% of time. Most spaces (12 out of 17, bold grey background) comply with the recommended range (17–21°C) for over 40% of time. All spaces (17 out of 17, green/yellow background) exceed 19 °C for more than 50% of time, and more than half (8 out of 17, yellow background) exceeds 21 °C for over 50% of time. Since the comfort threshold (>19 °C) and the recommended threshold (>21 °C) are excessively exceeded, it could indicate an overheating, as will be analysed in Section 4.6;
- December shows cooler conditions (average of 8.2 °C) compared to November (9.8 °C), leading to more hours of heating. Consequently, only A2, D2, D4, and D5 (blue background) remain below 17 °C for less than 3% of time. Nearly all spaces (15 out of 17, bold grey background) comply with the 17–21 °C range for over 60% of time. Almost all spaces (16 out of 17, green/yellow background) exceed 19 °C for more than 50% of time, although only A1 and B2 (2 out of 17, yellow background) exceed 21 °C for over 50% of time. This suggests that heating in December was used more appropriately than in November, although it would be worthwhile to quantify its potential savings, as discussed in Section 4.6;
- January shows even cooler conditions (average of 7.4 °C) compared to December (8.2 °C) and November (9.8 °C), resulting in more spaces (9 out of 17, blue background) falling below 17 °C. Almost all spaces (14 out of 17, bold grey background) comply with the 17–21 °C range for over 75% of time. All spaces (17 out of 17, green/yellow background) exceed 19 °C for more than 50% of time; and, again, only A1 and B2 (2 out of 17, yellow background) exceed 21 °C for over 50% of time. January is also the first month where no spaces record 0% in the 17–19 °C range, meaning all spaces comply with the 17–21 °C range for most of the time (grey background). Overall, these

January values are similar to those of December, which should be validated through the economic analysis in Section 4.6;

- February shows the warmest weather conditions (average of 10.3 °C), resulting in higher temperatures across all spaces. Very few spaces (only D2, D3, D4, and D5, and always less than 5%) fall below 17 °C (blue background). For most of the time (over 90%), all spaces are above 19 °C (green/yellow background). However, most of the time (only A1 exceeds 50%, bold grey background) it does not comply with the 17–21 °C range. Consequently, all spaces (17 out of 17, yellow background) exceed 21 °C for over 45% of time, with most (14 out of 17) over 60% of time. These results highlight the potential energy savings from heating management (turning it off during appropriate hours) and avoiding overheating on warmer days, as will be demonstrated in Section 4.6.

Table 3. Percentages of time in each range: (**a**) November; (**b**) December; (**c**) January; (**d**) February.

								(a)									
	A1	**A2**	**B1**	**B2**	**B3**	**B4**	**B5**	**C1**	**C2**	**C3**	**C4**	**C5**	**D1**	**D2**	**D3**	**D4**	**D5**
% <17 °C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.5	4.8
% 17–19 °C	0	0	0	49.9	0.7	0.5	0	0	1.8	6.4	1.8	0	1.0	2.3	11.6	20.0	24.3
% 19–21 °C	3.2	90.8	18.6	1.3	76.1	31.1	43.3	23.3	45.8	66.6	32.9	74.0	46.2	96.2	83.6	54.8	70.9
% 17–21 °C	3.2	**90.8**	18.6	**51.2**	**76.8**	31.6	**43.3**	23.3	**47.6**	**73.0**	34.7	**74.0**	**47.2**	**98.5**	**95.2**	**74.8**	**95.2**
% >21 °C	96.8	9.2	81.4	48.8	23.2	68.4	56.7	76.7	52.4	27.0	65.3	26.0	52.8	1.5	4.8	20.7	0
								(b)									
	A1	**A2**	**B1**	**B2**	**B3**	**B4**	**B5**	**C1**	**C2**	**C3**	**C4**	**C5**	**D1**	**D2**	**D3**	**D4**	**D5**
% <17 °C	0	2.8	0	0	0	0	0	0	0	0	0	0	0	2.9	0	0.7	0.3
% 17–19 °C	8.6	63.1	0	0.4	0.2	0	4.8	3.3	23.2	32.2	19.0	11.4	10.9	35.8	39.4	30.9	38.1
% 19–21 °C	20.4	34.1	71.3	31.3	98.1	61.4	65.3	70.0	54.6	67.4	60.8	70.9	77.9	61.3	52.0	60.6	61.6
% 17–21 °C	29.0	**97.2**	**71.3**	31.7	**98.3**	**61.4**	**70.1**	**73.3**	**77.8**	**99.6**	**79.8**	**82.3**	**88.8**	**97.1**	**91.4**	**91.5**	**99.7**
% >21 °C	71.0	0	28.7	68.3	1.7	38.6	29.9	26.7	22.2	0.4	20.2	17.7	11.2	0	8.6	7.8	0
								(c)									
	A1	**A2**	**B1**	**B2**	**B3**	**B4**	**B5**	**C1**	**C2**	**C3**	**C4**	**C5**	**D1**	**D2**	**D3**	**D4**	**D5**
% <17 °C	0	2.3	0	0	0	0	0	0	2.8	0.3	0	2.8	2.9	4.8	6.0	10.3	11.6
% 17–19 °C	18.1	35.9	18.1	5.4	3.7	5.8	9.7	20.4	27.6	43.1	20.3	20.2	22.5	60.5	46.5	22.8	42.9
% 19–21 °C	30.2	52.3	72.5	35.4	91.2	71.3	86.8	59.8	51.7	49.0	62.4	75.2	69.9	34.7	43.8	42.1	45.5
% 17–21 °C	55.3	**88.2**	**90.6**	40.8	**94.9**	**77.1**	**96.5**	**80.2**	**79.3**	**92.1**	**82.7**	**95.4**	**92.4**	**95.2**	**90.3**	64.9	**88.4**
% >21 °C	51.7	9.4	9.4	59.2	5.1	22.9	3.5	19.8	17.9	7.6	17.3	1.8	4.7	0	3.7	24.8	0
								(d)									
	A1	**A2**	**B1**	**B2**	**B3**	**B4**	**B5**	**C1**	**C2**	**C3**	**C4**	**C5**	**D1**	**D2**	**D3**	**D4**	**D5**
% <17 °C	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	3.1	4.9	1.3
% 17–19 °C	5.3	3.6	1.0	0	0.2	0	0.1	0.8	0.8	1.4	1.7	0.6	2.4	3.4	4.8	7.1	6.0
% 19–21 °C	49.1	30.6	17.3	6.0	10.4	4.1	12.8	16.0	12.5	20.3	39.1	12.3	34.3	30.8	27.3	23.5	41.9
% 17–21 °C	**54.4**	34.2	18.3	6.0	10.6	4.1	12.9	16.8	13.3	21.7	40.8	12.9	36.7	34.2	32.1	30.6	47.9
% >21 °C	45.6	65.8	81.7	94.0	89.4	95.9	87.1	83.2	86.7	78.3	59.2	87.1	63.3	65.6	64.8	64.5	50.8

4.6. Analysis of Economic Impact

Finally, to complete the study, an estimated calculation of the energy and economic cost of using heating when temperatures exceed the recommended threshold (>21 °C) is included. This calculation is carried out using the following methodology (see Table 4):

- From Table 3, the percentage of time in the bottom row (>21 °C) was converted into hours, completing the second column (time) of Table 4. This indicates the total hours above 21 °C (first row, yellow background) and provides a breakdown in 1 °C increments to estimate the potential savings with each additional degree due to heating;
- The IoT system monitored the energy consumed during each hour over 21 °C, and the cumulative value (MWh) is displayed in the third column (energy) of Table 4;

- Since energy costs fluctuate continuously based on market prices, the fourth column (energy cost) of Table 4 reflects the average value in euros per MWh (EUR/MWh), derived from the monthly report in [55];
- Finally, the fifth column (economic cost) of Table 4 presents the result of multiplying the third and fourth columns, providing an estimate of the potential economic savings that could be achieved by managing the heating to comply with recommended threshold (not exceeding >21 °C, first row, yellow background).

Table 4. Economic cost estimation: (**a**) November; (**b**) December; (**c**) January; (**d**) February.

(**a**)

Intervals	Time (hours)	Energy (MWh)	Energy Cost (EUR/MWh)	Economic Cost (EUR)
>21 °C	**29.9**	**7.92**	**63.44**	**501.97**
21–22 °C	15.7	4.15	63.44	263.21
22–23 °C	8.8	2.32	63.44	147.26
>23 °C	5.4	1.44	63.44	91.51

(**b**)

Intervals	time (hours)	energy (MWh)	energy cost (EUR/MWh)	economic cost (EUR)
>21 °C	**18.6**	**5.13**	**72.19**	**370.91**
21–22 °C	12.3	3.40	72.19	246.00
22–23 °C	4.7	1.30	72.19	94.07
>23 °C	1.6	0.43	72.19	30.82

(**c**)

Intervals	time (hours)	energy (MWh)	energy cost (EUR/MWh)	economic cost (EUR)
>21 °C	**16.5**	**4.49**	**74.09**	**331.79**
21–22 °C	12.6	3.41	74.09	252.74
22–23 °C	3.5	0.95	74.09	70.73
>23 °C	0.4	0.13	74.09	9.32

(**d**)

Intervals	time (hours)	energy (MWh)	energy cost (EUR/MWh)	economic cost (EUR)
>21 °C	**92.8**	**25.08**	**39.93**	**1001.31**
21–22 °C	34.3	9.25	39.93	369.39
22–23 °C	33.0	8.92	39.93	356.21
>23 °C	25.5	6.90	39.93	275.71

Following this methodology, the results for each month are analysed as follows (see Table 4):

- November. Temperatures exceed 21 °C (with heating on) for 29.9 h, where half (15.7 h) corresponds to the first degree (21–22 °C), monitored as 7.92 MWh. It means (estimating an average energy cost of 63.44 EUR/MWh) a potential savings of over EUR 500.
- December. Temperatures exceed 21 °C (with heating on) for 18.6 h, where the majority (12.3 h) corresponds to the first degree (21–22 °C), monitored as 5.13 MWh. It means (estimating an average energy cost of 72.19 EUR/MWh) a potential savings around EUR 370. As already noted in Section 4.5, in December, heating was used more appropriately (compared to November), as now quantitative demonstrated.

- January. Temperatures exceed 21 °C (with heating on) for 16.5 h, where majority (12.6 h) corresponds to the first degree (21–22 °C), monitored as 4.49 MWh. It means (estimating an average energy cost of 74.09 EUR/MWh) a potential savings around EUR 330. These values are similar to December, as noted in Section 4.5.
- February. Temperatures exceed 21 °C (with heating on) for 92.8 h, monitored as 25.08 MWh: the highest value, as noted in Section 4.5. However, the estimation in February of average energy cost decreased to 39.93 EUR/MWh, which represents an estimated economic cost around EUR 1000. Even so, it means a significant potential savings.

5. Discussion

Discussion about the obtained results (in previous Sections 4.1–4.6), concluded as following:

- When the heating is off, evolution of temperatures directly depends on weather conditions, following a thermal inertia around 2–3 °C above outdoor temperatures.
- When the heating is on, the building behaviour remains uniform in a range of approx. 6 °C. Thus, analysis of thermal evolution allows for the characterisation of working days (by monitoring their up-down trends which define sawtooth patterns), and identification of festive periods (by identifying significant drops in temperatures), even detecting anomalous situations (such as the opening of windows or doors, typical of public buildings).
- Thermal performance exhibits a characteristic morphology (regarding occupancy) with: linear behaviour (before occupancy), upward behaviour (due to occupancy), downward behaviour (after occupancy, that stabilises at a level similar to the initial linear behaviour), downward behaviour (between occupancy schedule, related to absence of people), and several non-pattern behaviours (related to unpredictable situations, as presence of people out of their schedule, detected by increasing CO_2 levels).
- Analysis of time percentages when temperatures fulfil the recommended thresholds (between 17, 19, and 21 °C) shows that majority of monitored spaces (out of 17; 12 in November, 15 in December, 14 in January) comply with the directives (17–21 °C) for most of the time (+40% in November, +60% in December, +75% in January). This is not the case in February since all spaces (17 of 17) exceed 21 °C more than 45% of the time (the majority, 14 of 17, +60%). This excess (>21 °C) is lower in previous months (out of 17, +50% of time: 8 in November, and only 2 in December and January).

The previous results quantify the potential savings from heating management (turning it off at the appropriate times) by estimating it as around EUR 500 in November (29.9 h and 7.92 MWh), around EUR 370 in December (18.6 h and 5.13 MWh), around EUR 330 in January (16.5 h and 4.49 MWh), and around EUR 1000 in February (92.8 h and 25.08 MWh). These estimations (indicative in themselves) are very significative extrapolated to every month and to all buildings on campus. This specific analysis, focused on temperature data, would require around 20 effective monitoring points. For this purpose, each sensor costs between EUR 100 and EUR 200, with a receiver station priced at approximately EUR 500. While the broader monitoring framework of the building incorporates a much larger network of sensors to gather additional data, the cost of the subset needed for temperature monitoring remains modest. This demonstrates that substantial Return of Investment (ROI) can be achieved with a targeted and cost-efficient deployment of monitoring IoT technologies. The results underscore the viability of such systems, for reducing energy consumption and associated costs, and also for contributing to broader sustainability challenges with minimal upfront investment in temperature-specific devices.

These results align with prior research on energy efficiency in Mediterranean climates. For instance, recent studies have demonstrated the effectiveness of integrating passive design strategies (such as double façades and photovoltaic systems) to reduce energy demand while maintaining thermal comfort [20]. Similarly, recent studies highlight the key potential of adaptive thermal comfort approaches, which consider behavioural adaptations to optimise energy use in various climatic conditions [26]. This work builds on these findings by incorporating IoT technologies to dynamically monitor and manage building conditions, allowing for real-time adaptability that enhances both energy savings and occupant satisfaction. The obtained results, although optimised for Mediterranean climates, have implications for broader climatic contexts. In colder climates, energy efficiency efforts should prioritise enhanced insulation and optimised heating systems: thus, IoT systems could focus on thermal retention and reducing heating losses. Conversely, in tropical climates, the emphasis would shift towards cooling systems, dehumidification, and natural ventilation strategies. For both cases, IoT-driven monitoring can dynamically manage energy use by responding to specific environmental conditions and building needs. Adapting this methodology to every region will require customised algorithms and sensor configurations that account for local climatic and cultural factors.

Further research should aim to validate the scalability of the proposed IoT-driven methodology in diverse climatic regions by exploring the following: (1) extreme climate adaptations: how applying adaptive IoT ecosystems in extreme environments (arid or polar regions) to test the robustness and flexibility of this approach; (2) cultural and regional variations: how socio-cultural factors influence energy use and thermal comfort preferences, and how IoT ecosystems can accommodate these variations; and (3) technological enhancements: how integrating renewable energy sources (such as photovoltaic panels) with IoT ecosystems to further optimise energy efficiency in varying climatic contexts.

6. Conclusions

The contributions of this paper help to comprehensively understand SBE complexity, by harmonising theoretical and experimental models and embracing multiple architectural diversity, moving towards hybrid twins. From a SBE conceptualization, merging its dynamic and adaptative perspectives by considering the human habitat, a SBE holistic definition is proposed as a multidimensional approach through six ways of inhabiting: defensive, projective, scientific, thermodynamic, subjective, and complex. Based on these premises, proposed IoT-driven solutions allow analysing the thermal performance (through real data from experimental measurements), quantify the potential of energy savings and estimate its economic impact. As previously discussed, the majority of monitored spaces comply with the directives (17–21 °C) for most of the time (+40% in November, +60% in December, +75% in January) while a month (February) all spaces exceed 21 °C +45% of time. These data quantify the potential savings as around EUR 2200: EUR 500 in November (29.9 h and 7.92 MWh), EUR 370 in December (18.6 h and 5.13 MWh), EUR 330 in January (16.5 h and 4.49 MWh), and EUR 1000 in February (92.8 h and 25.08 MWh). The extrapolation of these results to all buildings on smart campus and its application in public buildings would allow increasing energy efficiency by minimising the time when temperatures are above 21 °C with heating on while guaranteeing user thermal comfort.

These previous results quantify the potential savings from heating management (turning it off at the appropriate times) by estimating it as around EUR 500 in November (29.9 h and 7.92 MWh), around EUR 370 in December (18.6 h and 5.13 MWh), around EUR 330 in January (16.5 h and 4.49 MWh), and around EUR 1000 in February (92.8 h and 25.08 MWh). These estimations (indicative in themselves) are very significative.

A divergence between measured temperatures and normative thresholds has been observed. The main reason for this divergence lies in the complexity of space usage, the difficulty of fully sectorizing buildings, and the scheduling of heating periods (carried out weekly based on weather forecasts). This work demonstrates that implementing a more flexible heating system, rationalising space usage, controlling the doors, windows, and blinds openings, and integrating an IoT ecosystem (with real-time information on temperature trends, along with a heating on/off switching based on this data), would result in significant savings while improving user thermal comfort. In this way, for future research, authors are already working on smart algorithms to digitally manage the appropriate moments when heating is on/off switched following predictive models. This ongoing research will lead to adapting the proposed methodology to different contexts (such as residential or industrial structures) and integrate the deployed IoT ecosystem with emerging technologies (like Artificial Intelligence (AI), deep learning, and neuronal networks) for moving towards the novel paradigm of digital hybrid twins.

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