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The potential of smart home

For comfort and energy use optimization in residential buildings

2024 - Doctoral thesis

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THE POTENTIAL OF SMART HOME

For comfort and energy use optimization in residential buildings

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ABSTRACT

The design of a residential building to maximize comfort and energy savings is nowadays anchored in technical guidelines, although it is clear that individual preferences and subjective experiences play an undeniable role. Starting from this conflict, this study investigates the potential of new data sources (Internet of Things) and smart home technology as tools to better investigate and understand the real needs and preferences of individual inhabitants and, at the same time, to help the building adapt and respond to its occupants.

In many countries, environmental energy monitoring systems for residential buildings remain unregulated and are not mandatory, a situation attributed to the high costs, perceived invasiveness, limited flexibility, and ambiguous benefits to the end-users; consequently, even in optimal scenarios, their application is confined primarily to building managers rather than the actual occupants. With smart homes, the ability to collect data and information has exploded, as the number of low-cost sensors now available on the market. This has also led to widespread automation, with the ability not only to monitor but also to "control" the built environment. Alongside these advancements, however, lies the risk of accumulating vast amounts of data that are unmanageable and useless, lacking tangible significance. Concerns over privacy and loss of control over one's private living space are raising, coupled with skepticism regarding the true efficacy of these systems. To truly optimize building performance, particularly within the residential sector, it is imperative to first gain an in-depth understanding of the intricate interplay between the built environment and its occupants, select the right aspect to optimize, and then provide the necessary information for optimization to stakeholders.

Therefore, some questions arise: Is it possible, in the right situations, to use this less invasive and less expensive technology in place of more structured monitoring systems, the same ones also used in academic research? Is it a reliable technology? Can a monitoring system bring real benefits to the inhabitant and the building in terms of energy savings and quality of life improvement? Can it be adapted to the specific preferences and needs of both the building manager and the occupant?

The present study begins by examining the concepts of indoor comfort and energy use in residential settings from a new perspective, incorporating a systematic literature review that delves into socio-cultural aspects. Adopting an interdisciplinary "learning by doing"

approach, it deepens the topics of user-centered monitoring, the human-building interactions, and the wide-ranging resources and potential challenges that come with domestic environments.

To concretely answer the theoretical and technical questions raised, the study paired its theoretical analysis with the design and prototyping from scratch of a plug-and-play, low-cost, and non-invasive monitoring and automation system called MOQA, which leverages smart home technologies. This process facilitated a comprehensive understanding of the data lifecycle – from its production and collection to its management, presentation to key stakeholders, and final evaluation by the end-users – essentially assessing its utility. The deployment of MOQA across different case studies, alongside its evaluation against more conventional monitoring systems, enabled an examination of the system’s acceptance, functionality, user interaction, stability, and overall performance.

These experiences, despite some limitations, highlighted the user's pivotal role in effectively utilizing and truly benefiting from these systems. Support from individuals with in-depth knowledge of the system and its benefits is crucial, leading to satisfaction even among people who were initially skeptical. Over time, the system proved to be stable, accurate, accepted and, eventually, integrated into daily routines. Prioritizing hands-on solutions over theoretical debates about comfort and energy norms, the smart home system is perceived, in a personal parallel with the theory of salutogenesis in architecture, as a tool capable of connecting the inhabitant with the resources available in the building. Advancement in the spontaneous and beneficial exchange between humans and the environments they live in, spanning built and natural, leads to an uplift in the quality of life.

Overall, the doctoral study contributed to exploring the potential of smart homes by merging the perspectives of research and users and broadening the strictly economic and business vision currently associated with the topic. Scientific, industrial, social, and environmental implications were addressed, suggesting future lines of research.

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1 INTRODUCTION

"New technologies must enable people to live the life we all aspire to."

PROFESSOR H. ROSLING

The demand for energy-efficient buildings has become increasingly crucial in the face of climate change and the need for sustainable development: in 2022 buildings account for approximately 34% of the global energy consumption and for 37% of the global operational energy and process-related CO2 emissions [1].

Especially in a private space such as a dwelling, however, **is the inhabitant who consumes energy and not the building itself**. This is why occupant-centric performance-based design has been developed, with the aims to optimize the energy efficiency and indoor living quality of buildings with and accurate analysis of human-building interaction performance data.

Despite the growing adoption of sensors, actuators, and Internet of Things (IoT) devices in existing buildings and an increasingly monitored and controlled real estate sector, **having more data does not necessarily make it more valuable**.

This thesis discusses the use of IoT and smart home platforms for performance-based analysis in residential buildings, spanning the research domains of building construction, building physics, human science, and information and communication technology (ICT). The goal, which can only be achieved by considering the perspective of the end user, is to assess whether the reasons behind building data collection are aligned with the needs of the occupants (i), where this digitization process encounters barriers (ii), and if it is really able to provide useful advice and recommendations to building designers, energy managers, facility managers, and most importantly, occupants (iii), towards "*resourcient*" residential buildings.

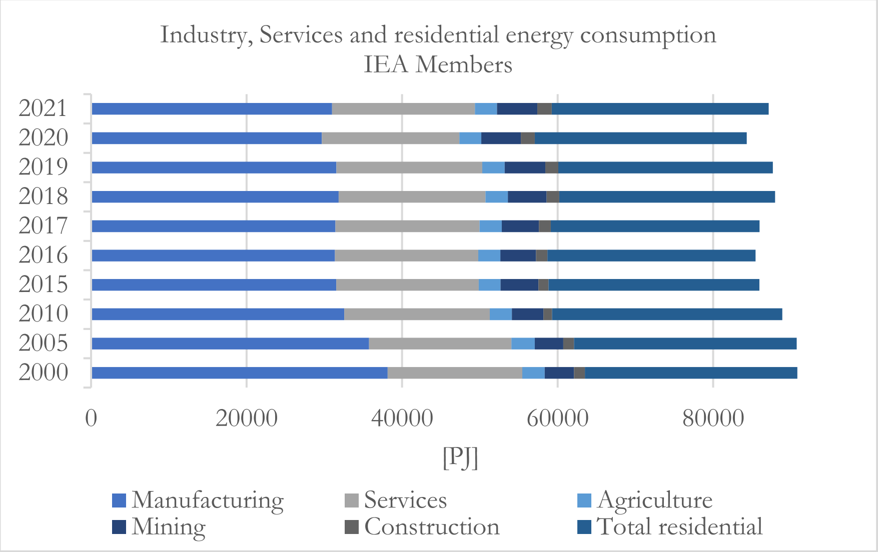
In the following paragraphs, clarified focus is made on why residences deserve more attention, what is meant by "*resourcient*" building and, more generally, what was the approach the work followed and what outcomes were produced.

1.1 Why residential buildings? Why Smart Home?

Understanding and analyzing energy consumption in buildings is a crucial aspect of sustainable development and energy management. However, the availability and comparability of energy consumption data, especially when divided by sector, poses significant challenges [2]. Existing studies and data on building energy consumption are often fragmented, making it difficult to find comprehensive and cohesive information. In addition, the task of comparing data from different sources becomes more arduous due to variations in the methodologies used for data collection [3], as will be demonstrated in the next few paragraphs.

One reliable reference for buildings energy consumption data is the International Energy Agency (IEA) [4], [5], although not all countries are included in the database.

Fig. 1.1 Energy consumption by sector – IEA Members. Source: IEA [5]



Focusing only on energy consumption and disregarding emissions, Fig. 1.1 illustrates the energy consumption by sector in IEA member countries[1]. The breakdown of energy end-use trends is based on the International Standard Industrial Classification (ISIC) of all economic activities [6][2].

Even with a global reference like the IEA, the data availability within specific regions, such as Europe, can present further obstacles. Direct comparisons between the IEA data and the EU building stock observatory [7] are difficult, especially since both include different member countries with different data collection methodologies [8], [9] and reporting systems. European data on buildings are also available in larger databases (Eurostat) or from other EU projects (Heat Roadmap Europe Project, Mapping Project, the EUCalc project, ODYSSEE-MURE, etc..). As evidence of this, Fig. 1.2 compares Italian energy consumption by sector using IEA data (Fig. 1.2a) and Eurostat data (Fig. 1.2b). The Eurostat data, which extend to 2020, refer to the NACE Rev. 2 classification [10] which unfortunately differs from the ISIC classification used by the IEA[3]. Limiting the analysis to the year 2020 and considering the "Total Residential" category, the Italian annual consumptions

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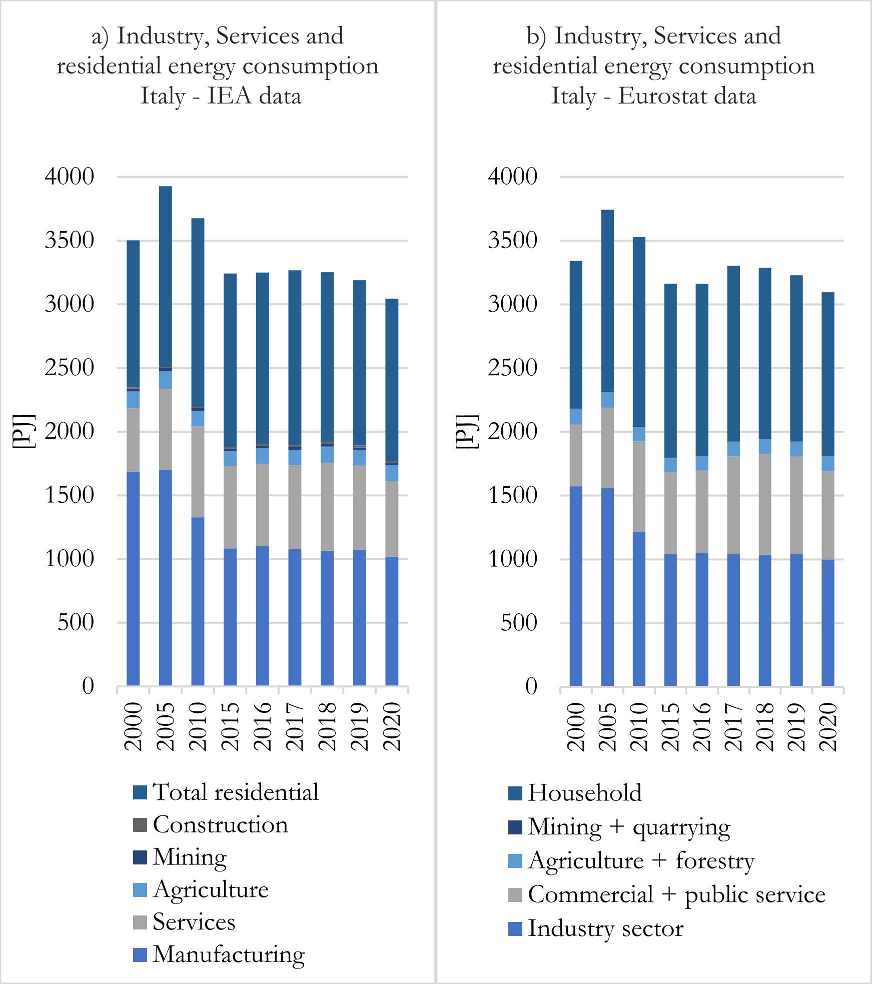
[1] Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Lithuania, Luxembourg, Mexico, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, The Netherlands, Türkiye, United Kingdom, United States

[2] More detailed information can also be found in the Energy End-Uses and Efficiency Indicators Database documentation [8]. The "total residential" category encompasses household consumption (Space heating, Water heating, Cooking, Residential appliances, Lighting, Space cooling, non-specified residential), excluding fuels used for transportation. It also includes households with employed individuals (ISIC Rev. 4 Divisions 97 and 98), which constitute a small portion of total residential consumption. The "Services" sector comprises commercial activities and public services (ISIC Rev. 4 Divisions 33, 37-39, 45-47, 52, 53, 55, 56, 58-66, 68-75, 77-82, 84 excluding Class 8422, 85-88, 90-96, and 99). This category encompasses not just building-specific consumption, including space heating, cooling, and lighting, but also non-building energy usage, categorized by activities (such as sewerage and waste management, accommodation and food services, information and communication, education, retail, health, and social care, among others). "Manufacturing" includes all manufacturing sub-sectors listed in ISIC Rev. 4 Divisions 10 to 18 and 20 to 32. "Agriculture" encompasses agriculture, forestry, and fishing (ISIC Divisions 01 to 03). "Mining" covers mining and quarrying, including coal, oil, and gas extraction (ISIC Divisions 05 to 09), while "Construction" includes ISIC Divisions 41 to 43

[3] In the NACE classification, the "Construction" flow is included in the "Industry" category, while "Fishing" constitutes a separate category (NACE Division 03 Rev 2) and is not represented in Figure 1.2b.

according to the IEA amount to 1275.6 PJ, compared to the 1283.5 PJ reported by Eurostat (-0.01%). However, in the "Services" sector, the difference is significant - 593.5 PJ compared to Eurostat's 693.2 PJ (-14.38%). This variation can be attributed to different methods of accounting for flows and a different total number of included categories[4].

Fig. 1.2 Energy consumption by sector – Italy.
Comparison between IEA data (a) [5] and Eurostat data (b) [11]



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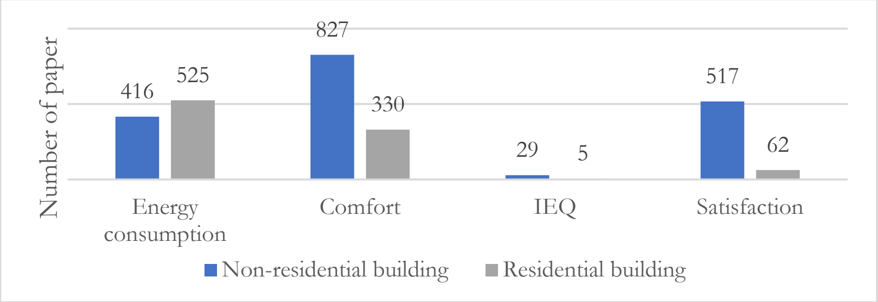
[4] Fortunately, in 2023, the NACE Revision 2 update 1 (NACE Rev. 2.1) [377] was introduced to align more closely with ISIC and it will be gradually implemented across all relevant statistical domains starting from 2025.

For a nation-by-nation exploration of the topic, useful references to individual databases are listed in [8]. Regarding Italy, as further evidence of the fragmented nature of available data, information can be found on the Ministry of Ecological Transition, Ministry of Environment and Energy Security (National Energy Balance) [11], TERNA, ARERA, RSE (Ricerca Sistema Energetico) and ENEA websites. In many cases, however, the focus shifts to evaluating regulatory parameters and the results of energy efficiency policies [12], [13], rather than presenting raw data. Both Fig. 1.1 and Fig. 1.2 illustrate how **residential buildings consume more in absolute value than commercial and service buildings**, primarily due to the greater number of buildings in this category. According to the European Building Stock Observatory [7], in Europe, in 2016, the number of residential buildings was 112,944,800, while non-residential buildings stood at 9,676,018 units, its 8.5%. More recent data is not available for all EU countries due to varying census intervals across different nations.

It should be noted, though, that monitoring the energy consumption of commercial buildings is often simpler compared to residential buildings, and this is attributed to several factors [14]. Firstly, commercial buildings, especially office spaces, are more likely to possess appropriate infrastructure, such as IT systems or Building Management Systems (BMS), that facilitate regular environmental monitoring. Conversely, residential buildings often lack these systems, resulting in challenges when gathering real-time data on energy consumption and environmental parameters. Secondly, in commercial buildings, there is a direct return on investment for employers through employee productivity and corporate wellness programs, which incentivizes the implementation of monitoring systems. The cost and complexity of equipment required for monitoring are relatively lower in commercial buildings compared to the diverse and decentralized nature of residential properties. Moreover, offices benefit from the advantage of observing large sample sizes, enabling simultaneous monitoring with a reduced number of sensors, thereby allowing for more efficient data collection and analysis. Studies focused on commercial buildings often leverage state-of-the-art sensing equipment that serves as reference standards, ensuring the reliability and accuracy of the collected data. Finally, sensors are frequently integrated into HVAC systems in offices, simplifying data collection and diminishing the need for additional sensor installations.

Does scientific research follow these trends? Is there greater interest in commercial buildings or residential ones? An exploratory research investigation was conducted on Scopus to discern whether the topic of indoor comfort and energy consumption is more extensively investigated in the context of residential or non-residential buildings[5].

Fig. 1.3 Number of papers related to energy and comfort topics for residential and non-residential buildings. Source: Scopus



The results (Fig. 1.3) shown that, when it comes to the energy aspect, the predominant attention does tend to align with residential buildings, primarily due to the well-documented fact that they indeed consume more energy. However, **a notable shift occurs when the focus moves to the realm of indoor comfort and Indoor Environmental Quality** (IEQ): the narrative changes and the spotlight in this context turns mainly towards office spaces. There are several factors that contribute to this shift in emphasis. As mentioned earlier, **non-residential buildings are generally easier to monitor than private homes**, but it is probably more important to note that improved comfort in these environments results in increased productivity [15], [16] , which bears significant economic implications [17]. While energy costs for a company represent 0.8% of operational costs, employee salaries and subsequently productivity account for a substantial 86.3% [18].

The **scarcity of case histories in residential settings can also be attributed to the inherently private, secure, and individualistic nature of**

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[5] Two search strings were employed: "(TITLE (office* OR ((non-residential OR commercial*) AND building*) AND …." and "TITLE (residence* OR ((residential OR domestic) AND building*) AND ….", corresponding to searches solely within titles for keywords related to non-residential and residential buildings, respectively. In place of the "…." in each search string, the terms "energy consumption," "comfort," "IEQ," and "satisfaction" were sequentially added one by one.

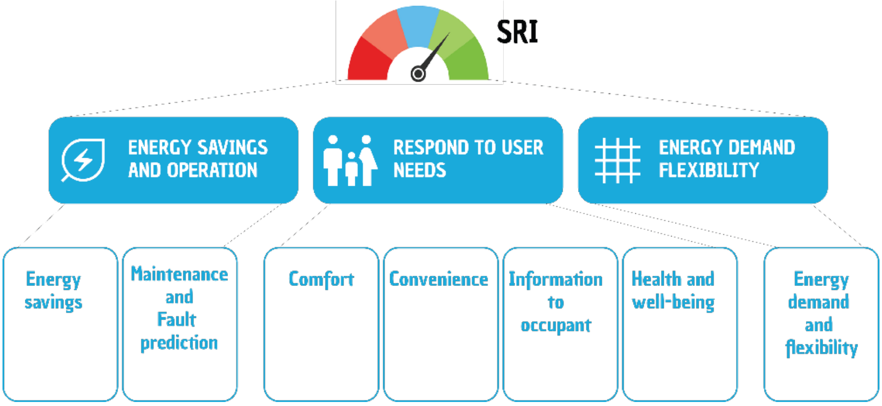
such environments. The inherent privacy associated with residential living renders the task of discerning consistent patterns and behaviors particularly challenging [19]. **Monitoring one's own home**, unless specifically requested, seldom appears as a helpful resource with tailored guidance to enhance building performance, but it **is frequently perceived as an attempt at surveillance**, judgment, and criticism of behaviors deeply rooted in cultural and familial traditions, which are often resistant to change, especially for long-term residents. Researchers often have disparate interests from those of occupants, whose perspectives and priorities are not always comprehensible to researchers, building designers, or operators, who have their own notions and criteria for evaluating proper building operation [20]. User priorities are intricate to categorize as they are significantly fragmented and contingent upon individual preferences. In contrast, commercial and public buildings, and notably office spaces, provide a more controlled environment for optimization due to their relatively structured and predictable nature, and this has attracted a lot of research attention. The topic of user behavior and **the interplay between comfort and energy consumption within residential spaces is thus comparatively less explored and calls for deeper investigation**, especially considering the significant amount of time spent in these environments. In comprehensive studies aimed at understanding individuals' daily routines and activity patterns [21] , both for the 9,196 individuals comprising the American sample [22] and the 82,095 European participants [23], it emerges that approximately 90% of time is spent indoors, with around 65% of that time spent within one's own home. **It is in our homes that our behaviors, interactions with the building, preferences, and beliefs take shape, and these drivers and behavioral patterns extend to all other indoor environments**.

To increase knowledge of the occupant-building relationship in the residential sector and optimize the comfort/energy use ratio, **the sole practical option seems to be utilizing minimally intrusive measuring tools**, essentially imperceptible devices **that users may already be familiar with** and that do not incite concerns or misconceptions like privacy-invading tools such as microphones or cameras [14]. IoT, particularly new smart home devices, embody these traits: compactness, user-friendliness, and user familiarity owing to their extensive commercialization and advertising. Occupants, possessing firsthand awareness of their home function and potential, may more readily appreciate the convenience of a monitoring system [24]. The outcomes of energy consumption education policies in residential settings have often fallen short. What if the approach shifted, rendering environmental energy monitoring attractive to end-users also through the tangible benefits of a commercial smart home product?

The penetration rate of smart home products in Europe is steadily increasing. In 2020, it was estimated that around 23% of households in Europe had at least one smart home device [25]. The most commonly adopted smart home products included smart thermostats, smart lighting, and smart security systems [26]. This figure was projected to grow at a compound annual growth rate of over 17% from 2021 to 2026 [25]. The number of smart homes in Europe has been on the rise, driven by factors such as technological advancements, increasing awareness of energy efficiency, and the desire for enhanced convenience and security [27]. The COVID-19 pandemic also played a role in accelerating the adoption of smart home technologies as people spent more time at home and sought ways to create more comfortable and efficient living spaces [28].

The integration of smart home technologies and their impact on sustainability, energy efficiency, and occupant well-being is nowadays increasingly being recognized in various building certification protocols. Although these certification protocols do not have specific criteria solely dedicated to smart home technologies, the principles and objectives of these programs often intersect with the benefits that smart technologies offer. Smart home technologies can contribute to energy savings, improved indoor environmental quality, and enhanced occupant experience – all of which are valued by these certification protocols. In terms of new standards, regulations, and certification protocols, the European Union has been actively working on initiatives to ensure the interoperability, security, and data privacy of smart home products. For example, The Smart Readiness Indicator (SRI) [29] is an innovative tool introduced by the European Union as part of its efforts to promote energy efficiency and sustainability in buildings (Fig. 1.4). It assesses a building's capacity to effectively use smart technologies and solutions to improve its energy performance, indoor comfort, user satisfaction and overall functionality. The objective of the SRI is to provide a clearer and more perceptible understanding of the enhanced benefits that smart building features bring to building occupants, tenants, owners, and smart service providers [30].

Fig. 1.4 Structure of domains and impacts criteria of the Smart Readiness Indicator



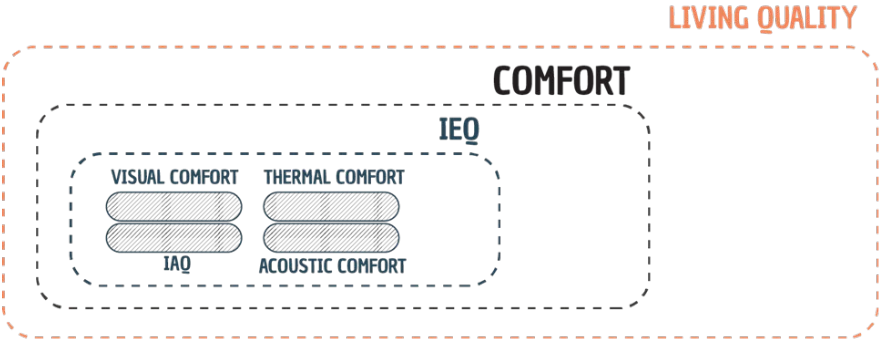
Within the realm of buildings, a symbiotic relationship exists among comfort, energy conservation, and technology. Differing from other applications like medical monitoring and security systems, building domain allows a slight compromise in precision in favor of affordability and user-friendliness [31]. **Wireless sensor networks emerge as a leading, adaptable choice for establishing cost-effective and easily deployable sensor networks in energy-intelligent building scenarios**. This validates the viability of harnessing widely available IoT and voice-controlled smart home products for research purposes, opening substantial possibilities for cross-disciplinary exploration. Today, although these devices exhibit potential, they remain in need of refinement, particularly concerning their capacity to gather data in a structured and cohesive manner. This shortcoming becomes evident when attempting to gather data from diverse sources, necessitating the use of various applications and systems. This fragmentation impedes a coherent and potentially powerful data collection process. Nonetheless, at a theoretical level, the concept of the smart home presents an intriguing prospect: *collaborative data mining* [32], a practice involving the application of data mining techniques across multiple data sources to unravel correlations and behaviors. Through collaborative data mining and well-organized databases, the results yielded by already widely adopted machine learning techniques could potentially lead to remarkable outcomes. In this context, the smart home assumes a pivotal role by expanding the spectrum of monitored buildings and individuals involved, while also sourcing data from traditionally unexplored avenues. Such avenues, sidelined due to concerns of cost, invasiveness, or technical challenges in conventional monitoring approaches, encompass dimensions like, for example, the consumption patterns of individual appliances, user satisfaction, and even surveillance systems. These data facets contribute profoundly to comprehending the intricate interplay between humans and the built environment.

1.1.1 Standard Definitions of Comfort and Energy Use

Buildings have traditionally been constructed to provide shelter from harsh weather conditions and to make occupants feel comfortable. However, understanding what "comfort" means and whether it's the same for everyone is essential when designing for users. The complexity of the topic, an incompletely structured literature and common terminology have led to an overlap of concepts that often causes confusion. Fig. 1.5, drawing on the literature, offers a framework for evaluation.

Discussing indoor comfort means addressing one of the topics that, along with safety and security, aesthetics, and functionality, falls under the concept of indoor living quality. This term generally refers to the overall conditions and characteristics of the indoor environment that influence the satisfaction of its occupants.

Fig. 1.5 Terminological framework for "Comfort" in buildings



Individually, the concept of comfort encompasses both quantitative and qualitative aspects. Its definition is not unique, but it often refers to standards such as ASHRAE 55, which deals primarily with thermal comfort but also offers valuable insights into creating comfortable indoor environments.

Thermal comfort is defined as "*the condition of mind which expresses satisfaction with the surrounding thermal environment and is assessed by subjective evaluation*" [33]. In this ASHRAE definition, two key elements emerge: satisfaction and subjectivity. Remarkably, objectivity assumes a less prominent role within the domain of comfort. Another definition, widely accepted by many scholars [34], suggests that defining comfort as the "*absence of discomfort"* is a simpler and more practical approach. It is associated with relief from physical symptoms, psychological and spiritual activities, and a sense of security. According to Pinto et al. [35] comfort is a broad holistic concept that encompasses the sensation of physical ease and bodily well-being. But what is well-being?

Well-being is '*the state of being comfortable, healthy, or happy', a concept related to happiness, positive experiences and pleasure with implications on physical, mental, social and environmental aspects*". [36] What is health then? WHO defines health as "*a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity*" [37]. All these definitions in the literature are often overlapped, blurred, and used interchangeably, not necessarily or solely due to researchers' negligence but due to the highly subjective nature of the concepts they convey.

Resuming the ASHRAE definition, it can be stated that all revolves around satisfaction, "*the good feeling that you have when you have achieved something or when something that you wanted to happen does happen*" (Oxford dictionary). **Achieving and maintaining comfort presents a multifaceted challenge** that necessitates a comprehensive understanding of various factors:

- Physical Phenomena
- Physiological Processes
- Psychological and Behavioral beliefs, attitudes, and responses to increase satisfaction

Considering physical-environmental and quantitative aspects, the term "comfort" is often associated with Indoor Environmental Quality (IEQ). Despite its consistently broad definition [33], both in academic discourse and, even more so, in professional practice, Indoor Environmental Quality refers to a series of calculable and monitorable physical-environmental parameters. IEQ is thus a subset of indoor comfort (Fig. 1.5) that, as mentioned, only takes into account the physical-environmental aspects. Numerous researchers attempt to provide their comprehensive overview of what IEQ encompasses

[16], [38]–[40], leading to a general definition that includes four key objective and subjective subfactors: Indoor Air Quality (IAQ), visual comfort, acoustic comfort, and thermal comfort [14]. However, the concept of IEQ can also be easily expanded: other mentioned physical parameters include water quality and electromagnetic pollution [41], to the extent that some authors have expanded the foundations of a healthy building to encompass nine distinct factors: Ventilation, Air Quality, Thermal Health, Moisture, Dust & Pests, Safety & Security, Water Quality, Noise, Lighting & Views [42].

From a physiological perspective, the multidimensionality of comfort arises from the complexity of humans and the intricate relationships between human systems (cardiovascular, digestive, endocrine, immune, muscular, nervous, reproductive, respiratory, skeletal, and urinary). Each of these systems has critical conditions under which it functions optimally, although science has not fully elucidated how each of them mutually influences the others. According to this approach, comfort is viewed as the attainment of equilibrium among various internal components within the individual and in their interaction with the surrounding environment. In practice, this has led to the establishment of certain standards and reference values for temperature, ventilation, noise, and light levels in design. However, there is nothing static in the human body (release and creation of cortisol, melatonin, alertness, body temperature) and in buildings (indoor temperature, received solar radiation, outdoor air infiltration): both humans and buildings periodically transition through numerous dynamic states to which we respond differently [43]. These responses, stemming from physiological factors as well as personal beliefs, attitudes, lifestyles, individual character, the location we find ourselves in, and social conventions, require the use of energy, both "internal" to our organism and "external" to the building or space in which we live. If I am dissatisfied with the room's temperature, I may adjust the heating system (external energy) or activate the internal mechanism of metabolism and blood redistribution (internal energy) to promote thermal comfort. If I perceive a high intensity sound, the stapedium muscle, located in the tympanic cavity, contracts or relaxes (internal energy), otherwise I close the window or door to minimize auditory perception (external energy). If the lighting level is insufficient, I adapt the pupils (internal energy) or, more likely, turn on the lights (external energy).

It is evident that comfort and energy become intertwined concepts, as will be further explored in Chapter 2. Nevertheless, it is essential to emphasize that this connection is intricate and not always straightforward: as per Knight and Rosa [44] and Akizu-Gardoki et al. [45], although higher levels of energy consumption can enhance well-being up to a certain threshold, there is evidence indicating that beyond this threshold, additional increases in energy consumption may not result in significant improvements in well-being (resembling the "plateau curve" [46]).

Adding complexity to this fact, **as with comfort, the definition of energy does not appear to be as straightforward as one might assume** [47]. The concept of energy is often used in its physical sense when referring to electricity, nuclear power, and energy reserves. However, despite its frequent use, even textbooks struggle to provide a clear and concise definition of what energy actually is. Energy is not a law of nature or something that has been observed or experimented with, but rather a label that we have created. It exists in various forms, such as kinetic energy (associated with motion), potential energy (associated with position or configuration), thermal energy (related to temperature), chemical energy, and more. These different forms can be complex and sometimes interconnected, making the concept of energy multifaceted. It can be stated that energy is an abstract concept: it is not something tangible that we can see or touch but rather a quantity that describes the capacity of a system to do work or produce changes.

The fact that comfort and energy use are influenced by subjective factors [48], [49] as well as building-related factors [38] has been extensively analyzed in the literature. This shift in thermal comfort research has prompted the development of personalized models [50], departing from those reliant on the thermal assessments of large and diverse groups of individuals. The fundamental characteristics of personalized comfort models include [51] : (1) focusing on individual analysis rather than populations or groups; (2) utilizing direct feedback and relevant data from individuals to train the model; (3) prioritizing cost-effective and readily obtainable data; (4) employing a data-driven approach, enabling flexible testing of various modeling methods and explanatory variables; (5) possessing adaptability to incorporate new data into the model. The primary objective of these models is to predict individual thermal comfort through machine learning models [52]–[55], correlating environmental measurements with occupant feedback gathered through surveys. Once the prediction proves to be potentially accurate, it can be translated into an algorithm that intelligently controls the building, particularly the HVAC system. The vision, especially in workplace environments, is to establish a pervasive system that allows occupants to customize and manage the indoor environment, akin to adjusting a seat on an airplane. In residential settings, however, this model may be more challenging to implement due to the involvement of less tangible and more sentiment-based variables.

1.1.2 Can a home be smart?

Before delving into how smartness and technology permeate the domain of residential environments, it is imperative to elucidate key terminologies that encompass this combination. The rapid succession of new approaches, tools and methodologies in recent decades has led to an overlapping of terms - "*smart*", "*intelligent*", "*sentient*", "*connected*", "*cognitive*" - that often generate confusion and different interpretations of the same concept of "building". Even when contemplating the concept of "home", various interpretations and meanings can be discerned, consistently present in academic literature over the past two decades [56]–[60]. All these publications, despite their different approaches and focuses, share a common recognition: that **the concept of "home" is intricate, multifaceted**, **and layered**, and that the used interchangeably and simultaneously in academic discourse and everyday language.

In the field of housing research, the most commonly employed term is "house", often used to refer to the physical structures where people live. However, this term tends to evoke the image of a specific Western-centric dwelling type, typically the detached single-family building. This narrow association makes it less universally applicable, as it fails to adequately capture the rich diversity of human habitation across different cultures and contexts. Acknowledging the limitations of the term "house" in encapsulating the entirety of human dwelling arrangements, Rapoport [61] introduced the more comprehensive concept of "dwelling". The term "dwelling" goes beyond the mere physical structure, encompassing all the various physical structures that individuals and communities use for habitation. It recognizes that our homes aren't just bricks and mortar but dynamic systems of settings within an environment. These settings are the stage for essential activities like eating and sleeping, as well as complex socio-psychological functions such as family life, safety, and privacy. A dwelling, however, can be regarded as a cultural artifact and only fulfils a subset of all the pertinent functions, which can vary between individuals and cultural contexts.

The concept of "home", along with its associated notions, interpretations, and meanings, has garnered significant attention in academic literature over the past two decades. "Home" is closely associated with positive emotions and emotional bonds. While "house" and "dwelling" referred to the physical structure, "home" encompassed the relationships with that structure and the meanings attached to it and is employed to describe a wide array of spatial entities, including the house, neighbourhood, town, state, and country [60], [62]. Researchers have examined the notion of "home" from various perspectives [63]. Some conceptualize it as a dynamic process that evolves and develops over time, whereas others [64] regard it as a stable and central place in the world that provides a sense of control over one's life and contributes to one's identity, reinforced by emotional and economic investments.

In the literature, the most widely accepted definition is the one adopted by the World Health Organization in 2011 [65]. It recognizes that "housing" encompasses four interconnected aspects: the physical structure of the house (or dwelling), the concept of home (a psychosocial, economic, and cultural construct shaped by the household), the infrastructure of the neighbourhood (the physical conditions of the immediate housing environment), and the community (the social environment and the population and services within the neighbourhood). Each of these four dimensions has the potential to influence physical, social, and mental health directly or indirectly, and the combined impact of two or more of them can be even more substantial.

As homes have shifted from being perceived merely as private sanctuaries rich in values to being viewed as "machines for living" [66], **technology** has unreservedly permeated every facet of architectural design, **progressively influencing our fundamental conception of dwellings**: in this context, the paramount goal has become efficiency. While achieving efficiency in housing design can be pursued through various avenues, akin to the complexity often associated with machinery, there exists a threshold that proves challenging for individuals to manage directly. Consequently, **terms like efficient, smart,**

and intelligent have become intimately associated with the concept of a "home", emphasizing a dwelling's capacity to respond immediately and autonomously to the occupant's needs. Numerous benefits of smart home and building systems have been extensively documented in various studies [67]. These advantages encompass enhanced personal thermal comfort and safety, reduced energy expenditures, and heightened adaptability.

Since the 1990s, **multiple conceptualizations and definitions of smart homes have been formulated and established** [68]. According to Gram-Hanssen and Darby [69], **a smart home** *"is one in which a communications network links sensors, appliances, controls and other devices to allow for remote monitoring and control by occupants and others, in order to provide frequent and regular services to occupants and to the electricity system*". As previously mentioned, much of the academic and grey literature in the field of energy assumes a close association between "smart" and energy efficiency. However, it's essential to note that this definition is not universally accepted as a standard and, moreover, it tends to overlook the role of occupants, often assuming that they are either unwilling or incapable of making lifestyle changes.

A more comprehensive concept is presented in [70], referring to "**intelligent** buildings": "*a multidisciplinary effort to integrate and optimize the building structures, systems, services and management in order to create a productive, cost effective and environmentally approved environment for the building occupants*". This concept is related to the idea of a "**connected** building", which involves linking a building to a network or external systems to enhance efficiency. However, this term is more commonly used when discussing the efficiency of a network of buildings rather than an individual one [71]. Another term, "**adaptive**", is employed when integration and optimization occur automatically. This is achieved through a building's ability to dynamically adjust its behaviour based on indoor and outdoor parameters using materials, components, and systems [72].

In all these definitions, it seems that the desires and needs of the user are delegated to an external intelligence capable of controlling the building, with the risk that this intelligence lacks flexibility and the ability to adapt to the ever-changing needs of the occupants: a **sentient** building [73] is one that "*possesses a sensor-supported, dynamic, and self-updating internal representation of its own components, systems, and processes. It can use this representation, amongst other things, toward the full* *or partial self-regulatory determination of its indoor-environmental status*". Wilson et al. [74] observed **a general lack of user-centric perspectives** and a tendency to treat homeowners as essentially passive, expecting them to adopt the automated solutions provided and use them as intended by the designers. The concept of "**cognitive**" [75], [76] takes a step forward from the static idea of the building as a container for human activities to a building capable of learning from users' behaviour and environmental variables to adapt itself to achieve primary goals such as user comfort, energy conservation, flexible functionality, durability, and maintainability.

However, this persistent pursuit of intelligence, efficiency, and technology should not stray from the concept of home outlined at the beginning of this paragraph. The home holds immense sentimental value and represents a cornerstone of private ownership, especially in the Western world. This is not easily reconciled with the possibility of external intelligences controlling something that rightfully belongs to us. Artificial intelligence reaches its full potential when it has access to data and information, when it can optimize a building's performance with a database of recurring patterns and usage modes, and when it can translate what it has learned into commands and algorithms that can be seamlessly integrated with other technologies, such as a structured HVAC system, capable of processing and interpreting data straightforward and immediately. This description may align well with work environments, offices, and commercial buildings. However, can we be equally confident that an occupant's interaction with their own home can be so neatly standardized?

Research suggests differently [77]–[85] and should lead us to **consider a different type of relationship between technology and a home's inhabitants**. A technology that serves on demand, silently suggesting and automating only when necessary, fostering the relationship between humans and buildings and helping users understand and enjoy the spaces they live in. **Can a dwelling be regarded as a repository of resources that occupants require, and can technology serve as the means to make these resources readily available to the end user in a convenient and understandable manner?** Such a dwelling would embody a harmonious fusion of technology and well-being, really functioning as a shelter that nurtures holistic physical, mental, and social health [86] . The concept of a *"resourcient"* ("resources" +

"efficient") building, fundamental to the entire thesis work, is further explored in Chapter 4.

1.2 Problem statement

Despite numerous advantages and advancements, smart home and IoT technology have not been widely embraced by ordinary consumers, and its potential to optimize energy efficiency and comfort has not been fully exploited. Several factors contribute to this phenomenon [87]: the adoption intention has been impacted by the reliability, performance, and controllability of IoT devices, often resulting in frustrating user experiences (i), the distance between certain users and technology (ii), financial considerations, such as high initial expenses including purchase, installation, operation, management, and maintenance, which outweigh the minimal and often hard-to-calculate savings, energy rebound, and wasteful consumption (iii), as well as concerns about privacy and security (iv). There are various solutions that could facilitate its usage [27]: (i) guaranteeing service scalability and diversity, (ii) increasing service accessibility, (iii) improving the work-life balance of potential users, (iv) ensuring long-term safety in relation to the use of systems and facilities, and (v) reducing the environmental impact.

As reviewed in Sections 1.1 and 1.2, research has largely focused on improving the technological aspect underlying the concept of smart buildings, with a particular emphasis on optimizing energy consumption and comfort in commercial or office environments. In these settings, the presence of centralized systems, scheduled activities, fixed hours, and limited user capacity and flexibility to modify the surrounding environment have favored the use of intelligent building management systems. However, a similar level of adoption has not been achieved in residential settings, mainly for two reasons:

A) **lack of a user perspective**

B) **it is neither clear nor easy to establish the actual energy savings brought about by these systems, nor how to assess the potential improvement in indoor comfort**.

A) There is often a limited awareness and understanding among users about the benefits and value of smart home technology services. In a residential setting, where diversity and flexibility of use are fundamental characteristics, IoT products may not always align with the unique needs and preferences of individual users. The focus is frequently on the technical aspects and improvements of the product rather than the personalized experience that users deserve based on their familiarity, inclination, and experience with technological systems. In many cases, technology is viewed with suspicion or, conversely, promoted as a universal solution to every problem. Striking a balance between user needs, IoT capabilities, and ease of installation and affordability is crucial. Informing users about the utility of data that a monitoring and automation system can process and leverage to enhance building performance and its indoor environment is essential. However, a fundamental question must be asked: What is the current utility of IoT-collected information for the end user? Is the user capable of effectively utilizing that information to manage their space sustainably and efficiently? The potential to improve the conditions of uncomfortable residential environments through data analysis should be explored, but privacy concerns may hinder “external intelligences” from accessing these spaces.

B) The challenge of determining the actual energy savings and evaluating potential improvements in indoor comfort brought about by IoT monitoring and automation systems is multifaceted. Firstly, the cost assessment of such systems typically revolves around their payback period, which is the time required for the system to offset its initial expenses. However, calculating this payback period for IoT systems is intricate due to the multitude of variables at play. These systems are influenced by factors such as the size of the building, patterns of usage, existing infrastructure, and the inherent efficiency of the system itself, making it challenging to accurately predict and quantify energy savings and Indoor Environmental Quality (IEQ) enhancements. The literature [88]–[90] mentions potential energy savings from 15% of up to 70%, but it frequently lacks clarity regarding the methodologies employed to achieve these savings. Few studies meticulously describe how the data was collected, and the extent to which user predisposition towards utilizing technological systems influenced these savings remains uncertain. Additionally, determining the initial costs of implementing an IoT system can be elusive, as these costs can vary significantly based on installation complexity and specific technologies used. Moreover, there is a lack of clear documentation regarding the additional energy consumption associated with operating IoT systems, encompassing aspects like data processing and communication.

1.3 Research approach

In the pursuit of the doctoral research, which centered on the optimization of energy efficiency and comfort in residential settings through smart home technology, a multifaceted approach was adopted to comprehensively address this complex and multifaceted challenge. This approach was underpinned by several key principles and methodologies that guided the development of a tangible technological solution.

Interdisciplinarity: Recognizing the inherent subjectivity of the concept of comfort, with its profound human, psychological, and social dimensions, the research topic was approached through an interdisciplinary lens. This involved melding the aforementioned aspects with the scientific rigor of engineering and the tools and techniques of Information and Communication Technology (ICT). By intertwining these disciplines, the goal is to provide a holistic perspective on energy consumption and comfort within the realm of building construction, encompassing the development of methodologies for measurement and optimization through data analysis. To be more specific, the multidisciplinary nature of the work is found in having coupled elements of technical architecture (see list of publications), ICT (development of the software and hardware part of a monitoring system) and investigations and methodologies from the field of sociological sciences (see Chapter 5 and 6).

Research and Innovation: The research adopted a pragmatic and innovation-driven approach. Rather than focusing solely on theoretical exploration, the emphasis was placed on the development of a tangible product serving as a solution to identified issues. However, the theoretical framework was meticulously defined, presenting a personal interpretation of energy consumption and comfort concepts in construction. This included methodologies for measurement and optimization through data analysis, resulting in the creation of a firsthand-developed solution.

Learning by Doing: The journey towards the solution adhered to a "learning by doing" approach[6]. The presented solution was informed by knowledge acquired through diverse research project – Dhomo, Renew-Wall, IsolMAX, M&asure, Contratti di quartiere II, ARV – followed during the PhD program and involving monitoring in various settings, techniques, and methodologies. While these case studies are not fully presented within the thesis, which maintains its central focus on the optimization of comfort and energy use, they are referenced in the list of publications. The development of the product presented in Chapters 5 and 6 likewise followed this approach. Technological advancements and enhanced efficiency were natural outcomes, driven by evolving expertise across different fields of application (Chapter 6). Collaborative efforts and engagements with entrepreneurial entities and startups active in the field provided insights into weaknesses and avenues for development.

Field Application and User-Centered Design: Practical application in real-world scenarios played a crucial role in refining the solution to align with user requirements in a genuinely user-centered approach. Direct interaction with end-users, including interviews and discussions, offered invaluable insights into the limitations and potential of the developed tool. This user-centric approach ensured solution relevance and facilitated continuous improvement and adaptation based on user feedback.

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[6] The principle of learning by doing has been advocated for thousands of years by many influential figures, such as Plato, Thomas Hobbes, English and Spanish epigrammatists, Karl Marx, Mao Zedong, cultural anthropologists, Montessori, John B. Watson (who is known for the phrase "Feed me on facts"), and B. F. Skinner [378]. The principle of learning by doing has been widely supported and expressed in various ways, such as learn-by-doing, trial-and-error learning, discovery versus instruction, practical experience versus book learning, the practice-theory-practice dialectic, and "proof upon practice". The positive aspects of the approach are not only emphasized by eminent scholars, but over the years, the application of the method has also found excellent results as a teaching methodology [379]–[381].
Having said that, the author not intended to imply that the learning by doing approach compromises theory in favor of practice. In fact, according to Lakatos, Popper, and Laudan, a theory is deemed effective if it generates empirically verified predictions, while transformative experimentation is deemed effective if it confirms or disconfirms expectations or predictions but leads to plausible adjustments of the underlying theory [378].

In summary, the research journey embraced an interdisciplinary, practical, and user-centered approach, underpinned by innovation and a commitment to learning through practical application. The resultant product not only addresses the intricacies of energy optimization and comfort in residential settings but also stands as a testament to the effectiveness of a multifaceted, holistic research methodology.

1.4 Research questions

The research conducted in this doctoral study introduces a fresh perspective on the optimization of indoor comfort and energy consumption in residential buildings. Departing from conventional approaches, a multidisciplinary framework is adopted to bridge the gap between building performance and occupant well-being. A significant aspect of this research is the exclusive focus on residential buildings. The study employs IoT technology as a central means to achieve its objectives. Through a user-centered approach it explores the potential of readily available IoT devices and mainstream smart home platforms as unintrusive monitoring and automation systems. The research critically evaluates the suitability of these commercially available products and modern voice assistants in an academic context. It seeks to determine whether these technologies can serve as reliable tools for collecting and analyzing data in the context of residential buildings. This approach is designed to address the typical skepticism and resistance often encountered when implementing monitoring systems in private residences. Finally, a key aspect of this research centers on the transformation of data into actionable insights. While data production[7] has become increasingly straightforward, the challenge lies in converting this information into practical recommendations and automations that homeowners can readily implement. This aspect of the study addresses a significant gap in current research and practice, with the aim of improving the quality of life in residential buildings while reducing energy consumption. The main research questions are therefore the following:

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[7] To elaborate on the concept of “data graveyard”, i.e., the risk that the ease of data production may result in data underutilization, see [382]

Can we really understand energy and comfort occupant preferences and building performance using IoT and smart home platforms?

This inquiry investigates the capabilities and limitations of IoT technology in capturing and interpreting data related to occupant preferences and building performance. It delves into whether smart home devices can provide accurate insights into how residents interact with their living spaces and whether these insights can genuinely improve comfort and energy efficiency.

How might IoT and smart home technology be used to improve comfort and reduce energy consumption in residential buildings?

This question delves into the practical applications of IoT technology, specifically mainstream smart home platforms, within residential settings. Its objective is to discern how IoT can be effectively leveraged to enhance indoor comfort while concurrently reducing energy consumption. The culmination of the study involves the development of a non-invasive, plug-and-play, open-source integrated IoT solution designed to actively engage and empower users. This solution provides information on energy consumption and offers suggestions aimed at motivating users to take a series of actions to reduce their energy usage.

Is the collection of comfort and energy data always effective?

This research question scrutinizes the effectiveness of data collection through IoT devices. It recognizes that while data collection may be feasible, it may not always yield meaningful or actionable results. It considers factors that can impact the reliability and validity of the data collected, such as sensor accuracy, data transmission, and the inherent variability in occupant behaviors and preferences.

1.5 Structure of the thesis

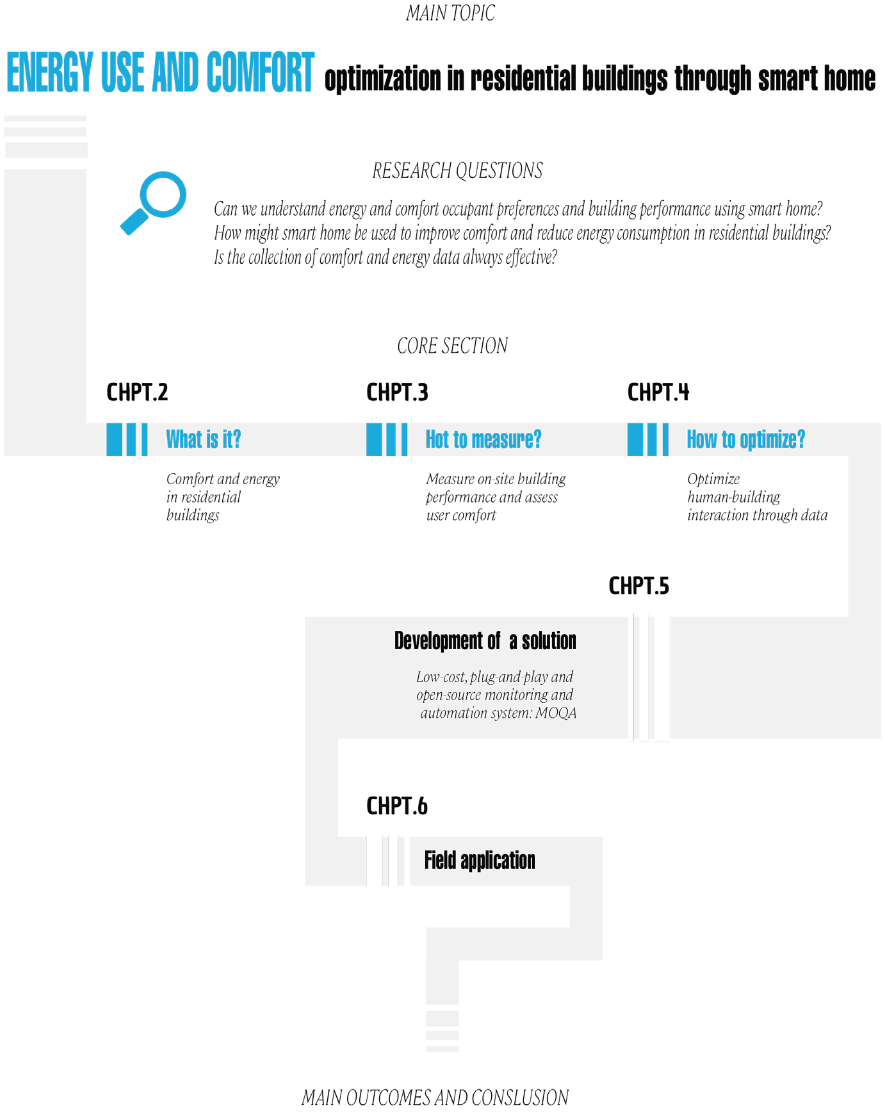
The thesis is deliberately not organized according to the classic introduction-methodology-results-discussion-conclusions structure. The choice, which is as ambitious as it is reasoned, is due to the desire to describe in the most appropriate way not a single project but a three-year journey, in which an extremely complex topic such as the relationship between indoor comfort and energy use in residential buildings and its optimization through data and the smart home was approached from multiple points of view, with multiple methodologies and multiple case studies. The dissertation is not presented as a collection of the articles published during this journey but as a narrative that, drawing from the experiences of various projects undertaken during the doctoral program, including those not here presented, weaves a cohesive thread and offers a unified vision on the subject, avoiding, by dwelling only on a single aspect, the risk, also personally found in the literature, of losing sight of the complexity of the topic.

The idea behind the chosen structure is as follows:

- Chapter 1 - Introduction: The topic and research gaps in optimizing indoor comfort and energy through smart home technology are described.
- Chapter 2: The meanings of comfort and energy in the classical definition are clarified, and a new approach to their conception is offered.
- Chapter 3: Methods for measuring indoor comfort and energy are described.
- Chapter 4: How to optimize indoor comfort and energy using data and smart home technology is discussed.
- Chapter 5: The comfort-energy monitoring and optimization tool, developed during the PhD, is described.
- Chapter 6: The application of the tool in various case studies is addressed.
- Chapter 7: Conclusions are drawn, identifying limitations and future developments.

This structure is graphically illustrated in Fig. 1.6. Not all parts of the work are the result of publications in peer-reviewed journals nor are they intended to be, but these are the parts that provide integrity and coherence to the entire discourse.

Fig. 1.6 Structure of the thesis



To facilitate the overall reading of the thesis, the traditional structure (introduction-methodology-results-discussion-conclusions), given its clarity, is still proposed within each individual chapter that delves into each stage of the journey in more detail. Following an introduction (Chapter 1) that outlines the research questions and clarifies the concepts used throughout the work, the various sections begin with some introductory notes and develop through the description of the methodologies and methods used for the analyses. They present the results, discuss them, and conclude with the main remarks.

In Chapter 2, a personal and multidisciplinary framework is provided for defining how to approach the topics of comfort and energy use in residential buildings, going beyond the common definitions found in major standards and regulations, already mentioned in section 1.1.1. Through a systematic literature review, particular attention is given to a more specific and in-depth examination of the socio-cultural factors influencing the perception of thermal comfort in indoor environments.

Once it is established what is meant by energy and comfort, Chapter 3 delves into how to measure these "variables", especially for existing buildings (i.e., in operation rather than in the design phase). The chapter introduces the potential of the smart home as a tool for monitoring and optimization (Section 3.4): the analysis of its pros and cons, which informs the rest of the work, stems also from personal experience gained in the field by designing and installing more traditional monitoring systems in other research projects. One of these systems is the one implemented in the Renew-Wall project, which is discussed in Section 3.5, specifically focusing on the monitoring of the designed building component. Here, the main technical challenges in the field implementation of an environmental monitoring system are quantitatively detailed.

After measuring the relevant parameters and obtaining structured data, the question becomes how to leverage this information. Chapter 4 highlights the need for an approach that places the user, not just the technology, at the center. It presents an alternative perspective on how to consider buildings, where optimization through data aligns with enhancing the interaction between humans and their built environment.

In Chapter 5, after a critical review of smart monitoring technologies already used in the literature, the reasoning about what is meant by comfort and energy use in a residence (Chapter 2), how to measure them (Chapter 3), and how to leverage data to optimize them (Chapter 4), flows into the solution developed during the doctoral research: MOQA. MOQA (“Misura e Ottimizza la Qualità della tua Abitazione” – “Measure and Optimize the Quality of your Accommodation”) is a home automation, open-source, highly customizable, and plug-and-play system for environmental and energy monitoring and optimization of indoor spaces. It serves as a hub that can connect almost every device and sensor, collecting data on energy consumption, temperatures, humidity, noise, lighting, indoor air quality, and much more. Based on this data, MOQA provides useful recommendations to enhance indoor comfort and reduce the environmental impact of daily actions. The system seamlessly integrates with all smart home platforms on the market, implementing actions or recommendations based on the data gathered.

Chapter 6 compiles insights and results obtained from the field application of MOQA in various case studies. The primary focus is on five apartments in public housing, but to improve the system, gather valuable feedback, and assess its flexibility, brief results from campaigns conducted in university classrooms, offices, laboratories, and a conference room are also presented.

In Chapter 7 the three initial research questions introduced in Section 1.5 are revisited and discussed based on the findings of the preliminary and core activities of the study. The Chapter also presents the findings of the study, examining environmental, economic, technical, social, and political-regulatory elements that may influence the attractiveness of solutions such as the one developed. It also outlines possible future developments for the system and research on the topic, for which the doctoral journey has laid the groundwork.

2 A NEW APPROACH IN CONSIDERING COMFORT AND ENERGY USE IN RESIDENTIAL BUILDINGS

"There is nothing like staying at home for real comfort."

JANE AUSTEN

2.1 Energy as a cost, comfort as a feeling

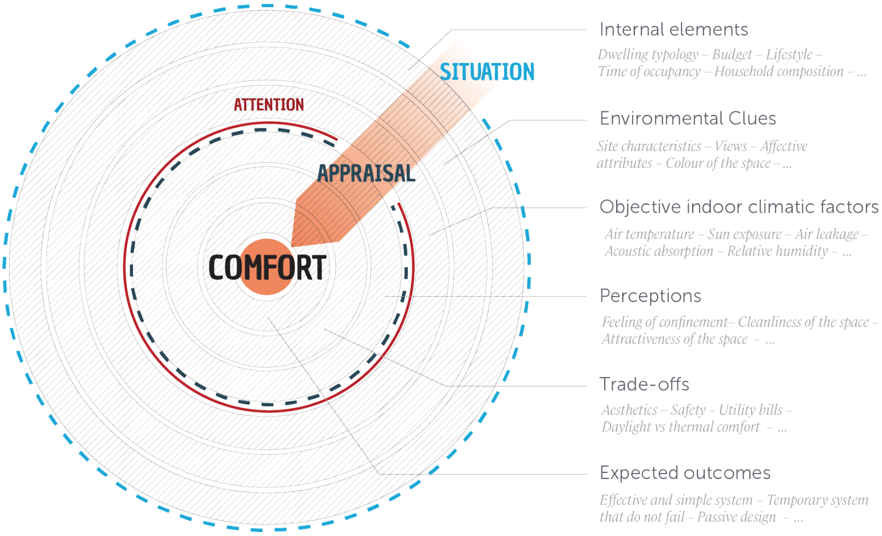
The concept of comfort/health/well-being associated with indoor spaces, as well as its intricate relationship with the resulting energy usage, remains fluid, contested, and controversial [43]. However, this paradox does not stem from ignorance, but rather often from pragmatism: building science tends to downplay "the mind" to avoid the overwhelming complexity it can introduce into both comfort research and practice [91]. The range of potential responses to achieve satisfaction in terms of comfort and energy consumption is much broader than what is currently considered in building codes and by those responsible for energy and environmental policies [92]. Energy-efficient buildings do not necessarily guarantee comfort [93] and, as highlighted in Chapter 1, dealing with residential or other inhabited enclosed spaces (offices, commercial buildings, etc.) is markedly different, especially in terms of occupants' perceived comfort and energy utilization.

The starting point, therefore, is a framework of complexity and an extensive, yet divergent, academic, and literary landscape on these subjects; the endpoint is the optimization of the comfort-energy relationship and the attainment of user satisfaction. However, these objectives cannot be detached from a clear understanding of what is meant by comfort and energy if the aim is to attain and maintain the former while reducing or balancing the consumption of the latter. Given this necessity, not again of ignorance but pragmatism, and exclusively within the context of residential buildings, with the intention, as also expressed in Section 1.3, of adopting a multidisciplinary user-centered approach and the "on the ground" perspective of the user rather than the technician [94], from this point forward, **a personal interpretation of the concepts of energy and comfort** will be used**: energy as cost, comfort as feeling**.

The concept of energy as cost arises from questioning how people make sense of domestic energy [95]. The answer is that, until now and until the eventual widespread adoption of digital displays and digital information**, the only way householders have to understand how they use energy to operate their homes is through their energy bills** [96]. For the end-user, bills represent money, and money signifies costs. Naturally, when considering other stakeholders, energy costs encompass more than just financial aspects.

The concept of comfort as a feeling, instead, is the result of a personal interpretation of the research conducted by German Molina [49], [91], [97], represented in Fig. 2.1 and available online, in its original version, with the name "Atlas of comfort" (https://buildingsforpeople.org/atlas.html).

Fig. 2.1 The Atlas of Comfort [84]: personal graphic representation



Comfort, in essence, is the result of how individuals perceive and interpret the situations they encounter. These situations encompass not only the physical environment, including quantifiable elements like objective climatic factors and less tangible aspects like environmental cues, but also psychological factors such as one's lifestyle, expectations, aspirations, and preferences, collectively referred to as internal elements. However, it's not automatic that every situation is inherently linked to a perceived and measurable level of comfort; rather, there must be a reason or stimulus that captures the individual's attention and triggers a sense of (dis)comfort. According to Molina, the probability of a situation capturing a person's attention depends on how occupied they are and their satisfaction with the space. Once a situation captures their attention, individuals assess the comfort of the space through three appraisals: perceptions, trade-offs, and expected outcomes. Perceptions involve the meaning individuals assign to their sensations [98], specifically the interactions between their bodies and the environment. Trade-offs reflect the holistic assessment of comfort, including its connection to the aforementioned energy consumption, considering that individuals understand that certain actions, like opening windows, can enhance specific facets of their well-being, such as cooling down an excessively warm living space, but those actions may also have adverse effects on other aspects of their lives, such as introducing noise and insects into the indoor space or increasing energy bills. Expected outcomes consider the inferences individuals make about their future, as they try to predict the likelihood of encountering specific situations, influencing their overall evaluation of the environment: the best-case scenario is that in which situations that are expected to remain comfortable without requiring human intervention. A dwelling that fulfills these three conditions is considered comfortable, implying it provides three primary advantages: **mental well-being, physical well-being, and** the **freedom** to maintain a certain lifestyle without the dwelling acting as a barrier (Fig. 2.2).

Fig. 2.2 The concept of comfort as a feeling

It is precisely this sense of freedom that constitutes the novelty of the model, from which two key insights can be derived: (i) not all situations prompt people to assess their comfort levels and therefore research should not aim to assess every possible situation; (ii) as indicated by ASHRAE, comfort is typically perceived by the average user as the absence of discomfort or nuisance situations. Rather than delving into the definition of discomfort, the focus should be on designing environments that, by avoiding stimulating "attention", should remain comfortable without any kind of intervention. Alternatively, it involves designing and ensuring the availability of effective and simple systems that can quickly assist in resolving potential issues.

2.2 Background: the role of culture in shaping environmental perceptions in buildings

The Atlas of Comfort introduced in the previous section integrates comfort and energy consumption concepts in residential settings, offering a fresh perspective for analysis. However, also this model has some limitations, the most significant of which becomes evident when attempting to apply it to the design of a residential space where multiple people live, and where perceptions, trade-offs, and expected outcomes vary from person to person: to design shared spaces, it is necessary to work with clusters or groups of individuals. The probability that similar expectations and satisfaction levels coexist in a home is not necessarily low, considering that these subjective values can be shared within a family living under the same roof. On the other hand, however, the literature is limited and offers little support when investigating how those values and socio-cultural factors influence comfort among different groups of individuals. Indeed, when considering the context of a condominium or neighborhood, as opposed to individual residences, the comprehension of how individuals from diverse backgrounds, encompassing not only their country of origin but also their broader cultural contexts, perceive comfort becomes a pivotal consideration.

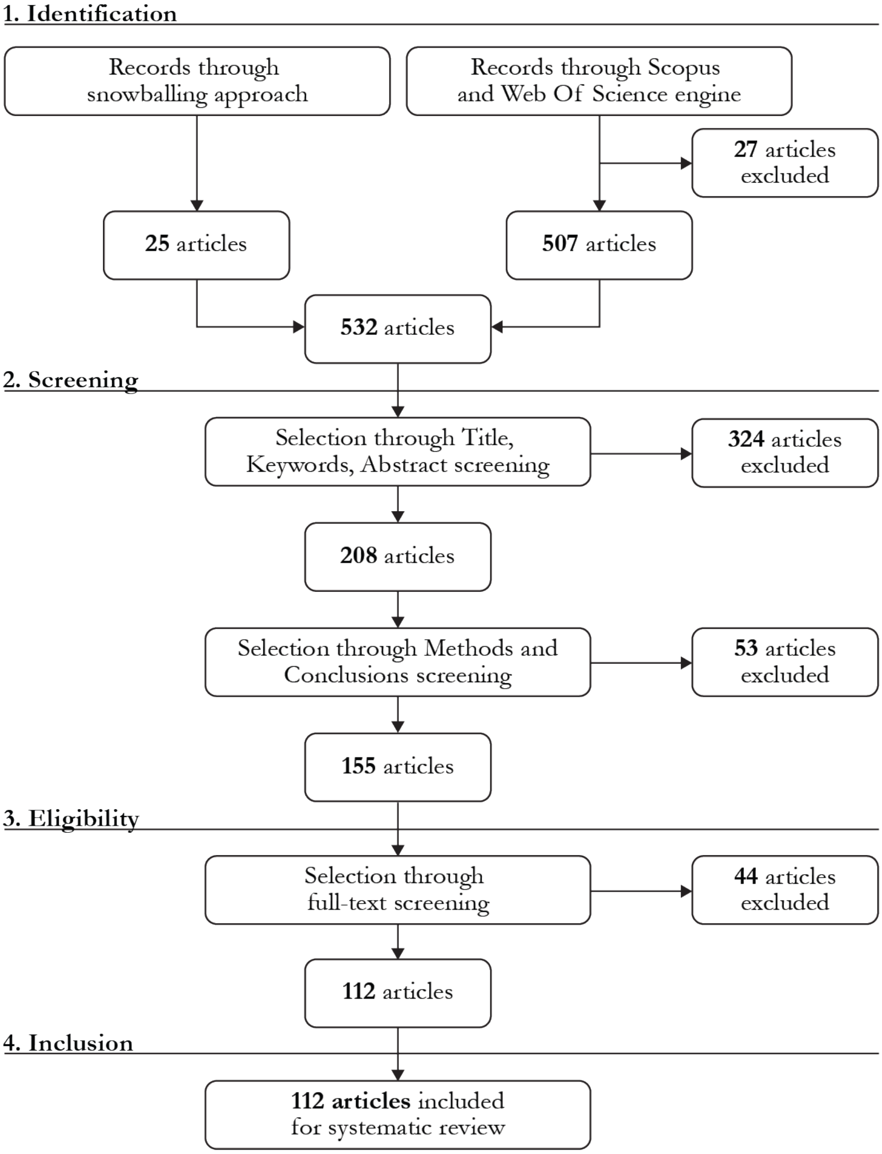
Beyond physical and environmental variables, what parameters influence the perception of indoor thermal comfort within a given social community? Do they differ from one community to another? Among these parameters, which are influenced by cultural backgrounds? Are they comprehensively addressed in the current literature, and if so, how? Alternatively, are they overlooked or neglected? Existing reviews that address thermal comfort and cultural factors in indoor environments tend to focus on specific population segments, such as elderly individuals [99], women [100], or focus on outdoor environments [101], [102], energy-related issues [103] and cooling conditions [81]. Additionally, some reviews are outdated [104], [105]. There is no shared model, methodology, or comprehensive list of aspects to investigate, and different communities or groups of individuals are not directly compared unless considering one aspect at a time. Furthermore, categories typically perceived as more objective, such as gender, age, and climate, which are already included in traditional thermal comfort evaluation models, should also be addressed from a subjective point of view: for instance, clothing choices may vary not only based on climatic and environmental thermal conditions but also due to cultural factors.

In the following sections, a systematic literature review is presented concerning the role of socio-cultural factors in influencing indoor comfort. Given the extensive scope of this topic, the analysis is focused solely on thermal comfort. Although the focus is limited to a single domain, thermal comfort is recognized still as the most relatable and appreciated aspect by users, serving as the foundational reference point for their perspectives. The primary objective is to provide a comprehensive overview of the aspects under consideration and to highlight their methodological examination in the literature. This framework, apart from fostering more productive collaboration between researchers and technical experts engaged in thermal comfort design with social scientists, can establish the groundwork for developing a shared platform or tool that would help designers working on social housing, urban and building redevelopment projects, as well as institutions responsible for allocating accommodations to individuals in need, to make more informed decisions.

2.3 Methodology

The literature review is organized as a Systematic Literature Review (SLR) [106] of papers on socio-cultural factors influencing indoor thermal comfort.

Fig. 2.3 Flowchart of the articles' selection process.



The article selection methodology is based on the Preferred Reporting Items for Systematic reviews and Meta-Analyzes (PRISMA) guidelines [107]. Fig. 2.3 shows the research approach marked by stages of data processing, i.e., identification, screening, eligibility, and inclusion. The identification of the articles to be analyzed was carried out through a series of searches in the Scopus Elsevier and Web of Science databases, consulted for "title - abstract - keywords" research, with the last update in December 2022. The search strings, keywords and synonyms used are shown in Tab. 2.1. The search resulted in 507 documents, taking into consideration all types of publications with no timespan limits but removing the overlapping studies between databases. Subsequently, the search was expanded through the snowballing citation approach, which was performed by analyzing the references of particularly relevant articles and more contemporary publications that cited the starting point articles and through the examination of international research project reports. Through this procedure, 25 potentially relevant documents were selected.

Tab. 2.1 Search queries

Thermal comfort	*AND Indoor*	*AND Culture*
"thermal comfort" OR "thermal behaviour"	indoor OR building* OR construction* OR "house" OR "offices" OR "built environment"	cultur* OR multicultural* OR ethnicity OR socio* OR demographic

For a thorough understanding of how the topic developed around the world, the research incorporated references from various geographical domains. Overall, journal articles, conference papers, reviews, and book chapters are the primary sources of information.

A preliminary selection among the articles collected, through an evaluation of the title, keywords and abstract, was conducted. Tab. 2.2 and Tab. 2.3 shows the inclusion and exclusion criteria used by the authors for the screening process.

Tab. 2.2 Inclusion criteria definition and justification

Criteria	*Range*	*Justification*
Research scope	Socio-cultural factors influencing indoor thermal comfort	Review of cultural factors influencing outdoor thermal comfort already published by [101], [102]
Topics	Intended use (dwellings, schools, offices)	Built environment experienced by users not sporadically and with possibility/authorization to intervene for improving thermal comfort conditions (for instance, museums, churches, and other intended uses like these were excluded)
	Climate	Differences among climatic zones or countries and within a single country
	Age	Differences among young people, adults, and the elderly
	Gender	Difference between male and female
	Habits at home/school/work/other	User personal actions to improve his thermal comfort
	Activities at home/school/work/other	In terms of metabolic rate and socio-cultural meaning
	Clothing	Differences due to traditional clothes
	Low-Income	Influence of energy poverty
	Educational attainment	Level of education and awareness on the topic of thermal comfort
	Thermal history	Influence on expectations and preferences
	Language	Differences in the description of comfort perception due to linguistic reasons
	External factors	Influence of commercial/social trends and sustainability issues
	Psychological factors	Sense of belonging, emotions, stress (at the group level and not at the individual one)
	Surroundings factor	Influence of sound, light, or other factors
	Possibility to modify the environment	Soft or radical interventions to achieve thermal comfort
	Immigration	Different perception of users from different countries

	Vernacular architecture and traditional lifestyles	Construction solutions, materials, architectural layouts, and ways of living typical of each culture
	Methods to acquire socio-cultural factors	Questionnaires or other solutions
Timeframe	No limits	The absence of previous reviews on the subject did not lead to set time limits
Geographical Context	Worldwide	Required for the review aim
Language	English	For a better evaluation of the full papers by this review authors. Nevertheless, since abstract and keywords are usually provided in English language, in the first phase of publications screening through "Title, abstract, keywords" also studies with full papers written in a language different from English were included
Scientific	Journal articles, Conference Proceedings and Books	Research satisfying scientific criteria

Tab. 2.3 Exclusion criteria definition and justification

Criteria	*Range*	*Justification*
Topics	Studies only related to adaptive comfort	Need to intercept only studies that analysed the influence of socio-cultural factors on internal thermal comfort
	Retrofitting of cultural heritage	Off-topic
	Studies with a technical focus on the design strategy/solution	Off-topic
	Objective measurements only	Off-topic
Language	English	For a better evaluation of the full papers. Nevertheless, since abstract and keywords are usually provided in English language, in the first phase of publications screening through "Title, abstract, keywords" also studies with

		full papers written in a language different from English were included.

At this stage, 324 papers dealing with outdoor comfort, heritage buildings, and objective measurements were excluded because they did not meet the search criteria. A furthermore in-depth evaluation was carried out by analyzing the method and conclusion sections, thus excluding other 53 articles. Finally, the 155 selected articles were analyzed through a full-text reading, which led to the definitive inclusion of 112 articles in the presented systematic review.

After the data filtering process, a bibliometric analysis of the investigated documents was conducted. The VOSviewer software (version 1.6.18) was used for this analysis since it allowed for the creation of maps of the research regions of the examined texts based on the co-occurrence of keywords, starting from a .ris (Research Information System) file.

With the aim of contributing to the development of a conceptual framework that helps promote coherence in future research, suggesting directions, and identifying specific areas where further studies or investigations may be needed, the results, described in the following section, are organized into 7 main categories:

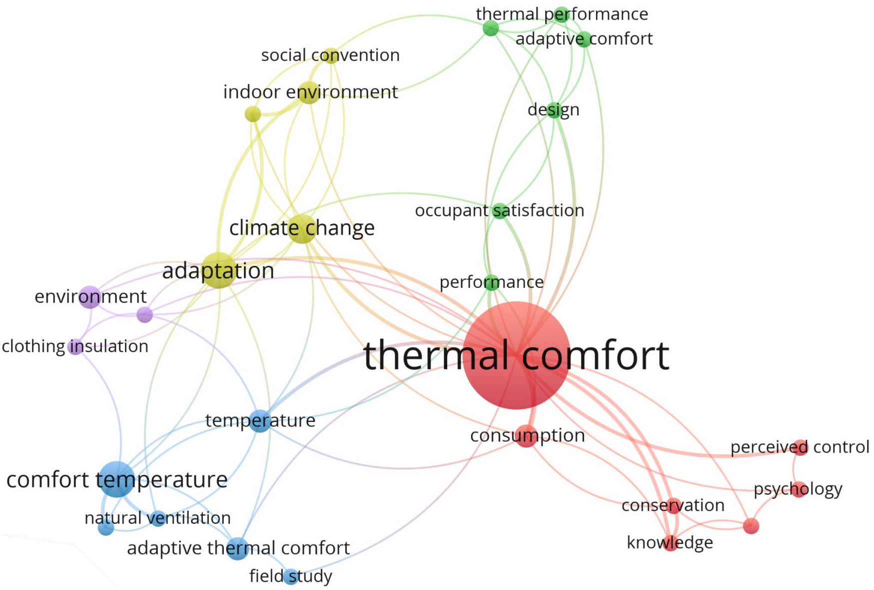
- Climatic and environmental issues;
- Demographic factors (age and gender);
- Body Composition and Physical Activities;
- Habits and ways of human-building interaction;
- Contextual factors and socio-physiological aspects;
- Income and education level;
- Language.

2.4 Analysis of socio-cultural factors influencing indoor thermal comfort

2.4.1 Bibliometric analysis results

Fig. 2.4 displays the outcomes of the bibliometric analysis performed on the 112 documents chosen for the review.

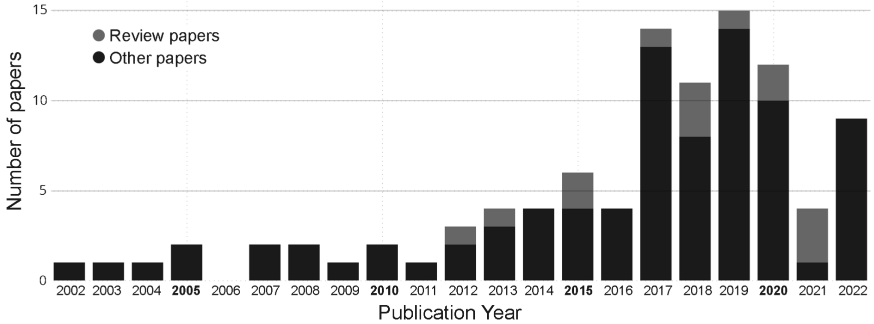
Fig. 2.4 Bibliometric analysis of the selected documents in VOS-viewer (112 documents, minimum 3 co-occurrences, 27 keywords).



27 terms are included in the map, which considers the chosen texts and is assessed using a minimum co-occurrence value of 3. This analysis included significant keywords like “thermal comfort” and “occupant contentment” but also “psychology” and “social convention”. Five distinct clusters were found: the red cluster deals with psychological topics and perceived comfort, the green cluster is about thermal comfort evaluation models, the blue cluster is about physical characteristics like temperature and ventilation, the yellow cluster is about climate change and its social effects, and the violet cluster is less significant. Fig. 2.5 shows a significant growth in the number of articles during 2017: this may be attributable to the SDGs being adopted by the United Nations beginning in 2015 and the ensuing rise in interest in the comfort issues in social housing as they relate to the sustainable development of cities and

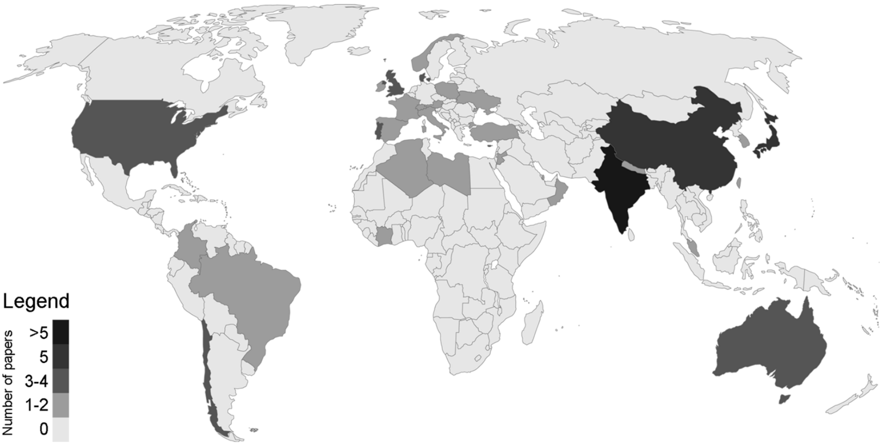
communities as well as the fight against poverty. On the other hand, the recent expansion in the publication market could be blamed for this trend. Journal articles comprise most of the included publications, accounting for 90 of them compared to 12 conference proceedings, 3 reports, 1 book, and 1 book chapter.

Fig. 2.5 Number of examined papers per year.



The selected papers were chosen from various locations around the world. Asia is the region where most articles are frequently published, with India, China, and Japan contributing a significant number of research papers on the topic. On the other hand, there are some regions not analyzed due to a lack of research resources. Fig. 2.6 displays the origins of papers that focused on applied studies related to thermal comfort in diverse climate zones, resulting in a varied and extensive study sample. However, there is a clear lack of studies in many countries, which therefore does not allow the present study to delve into socio-cultural aspects related to many areas of the world.

Fig. 2.6 Number of examined application papers by country.



2.4.2 Systematic literature review results

Climatic and environmental issues (n. of paper = 55)

Climatic conditions are widely recognized as significant drivers affecting variations in thermal comfort evaluations, and there is strong evidence that our assessment of thermal comfort is influenced by both short-term and long-term climatic backgrounds. In a study examining the impact of climatic backgrounds on in-the-moment thermal comfort experiences, Jowkar et al. [108] collected and analyzed data from a subset of 1225 students who had resided in the UK for less than 3 years. These students were categorized into three main groups based on their origin climates. Overall, when exposed to the same thermal environment, participants with a warmer "thermal history"[8] reported feeling cooler compared to their counterparts in the similar-to and colder-than-UK thermal history groups. Ji et al. [109] demonstrated that when individuals transition from one environment to another with a different temperature, their previous thermal experiences may result in different feelings and impact their evaluations of thermal comfort. They conducted experiments in a climate chamber, with a total of 8 experimental conditions, involving temperature variations. When transitioning from a cold/hot environment to a neutral one, or from uncomfortable to comfortable, thermal sensation improved.

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[8] The concept of thermal history is well elucidated in [132], where the authors explore if it is "possible that people living in 'ideal' indoor climates for a long periods have higher and higher thermal expectations causing them to become increasingly "fussy" about their thermal environment, resulting in no increment in satisfaction, or sometimes even decrements in satisfaction compared to their counterparts occupying environments with much greater dynamic thermal range".
The article, through the analysis of questionnaires administered to four subject groups totaling 1140 participants, concludes by stating that "Long-term thermal experience appears to shift occupants' thermal expectations, and apparently it is much easier and quicker to lift comfort expectations than it is to lower them." This correlation is also investigated in [383] and [384], where the following definition of thermal history is found:
"Thermal history refers to the previous thermal conditions experienced by individuals. It influences current thermal perceptions by providing a benchmark or experiential calibration frame of reference. It can be divided into:
-Short-term thermal history: Referring to effects across timescales ranging from weeks, days, hours to seconds in day-to-day thermal exposures.
- Long-term thermal history: Referring to the climatic influences of where people have been living for some years."
It is on this latter aspect that previous life experiences (where I have lived, how, with whom, under what conditions) have an effect.

How people adapt to specific thermal conditions can differ between countries and regions. Zhang and de Dear [110] utilized the largest global thermal comfort database to date (ASHRAE Global Thermal Comfort Database II), examining the influences of various demographic and contextual factors, including gender, ventilation mode, building type, season, and climate, on occupants' thermal sensation. Their dataset included data from Asia, Europe, Oceania, North America, South America, and Africa, encompassing 107,583 records from 98 cities in 28 countries across 16 Köppen climate types. Their findings revealed that residents in warmer climates perceive the same indoor thermal environment as significantly cooler than those in cooler climates, with this climatic adaptation being more pronounced in females than in males. Zhou et al.[111] compared Western comfort evaluation models with a thermal sensation model developed specifically for predicting the thermal sensation of Chinese individuals. Their modified Chinese model demonstrated better predictions, with differences in thermal sensation between predictions and laboratory and field study results being less than 0.5 scale units. Also Brambilla et al. [112] sought to evaluate whether a European standard could be universally applied across continental and Mediterranean climates. They used the RhOME prototype, a single-family detached house, as a reference building for their analysis, simulating it in four different European locations with varying climatic contexts. The authors suggested that traditional set-points and thresholds used in simulations may need adjustments: for instance, maintaining an internal temperature below 25°C might be perceived as overcooling in hot regions, leading to excessive cooling loads. Although their work relied solely on simulations and lacked field validation through monitoring or post-occupancy evaluation, it intriguingly suggests that flexibility in the evaluation method and standards should be ensured to accommodate the diverse socio-cultural contexts across Europe.

In a cross-cultural analysis of household energy use behavior in Japan and Norway, Wilhite et al. [113] demonstrated how cultural values associated with technology choices for heating, as well as the methods and quantity of heating provided, can vary between countries. Comfort, here, takes on different symbolic and subjective values: in Norway, the combination of space heating and lighting contributes to creating an ambient atmosphere known as "koslighet", which is virtually obligatory for living rooms. A similar comparison is also illustrated in Kuijer & de Jong [114], who, when comparing Japan and Germany, find that the Japanese generally and historically adopt more person-oriented heating practices, with a great diversity of more localized heating systems such as "hibachi," "yuutampo," and kotatsu".

Other studies have explored geographical and seasonal differences in comfort perceptions within the same country. Singh et al. [115] conducted comfort surveys and long-term thermal monitoring of vernacular houses across various climatic zones in Northeast India. They concluded that it is not feasible to create a generalized thermal comfort model for all climatic zones due to region-specific adaptation processes, including clothing choices, expectations, and perceptions driven by local socio-cultural requirements. A similar conclusion was reached by Kumar [116], who analyzed Indian field data from the ASHRAE Global Thermal Comfort Database-II. Kumar, as well as Indraganti [117], found that thermal acceptability ranges for Indian subjects differ significantly from international comfort standards due to the wide and culturally diverse climatic zones found in India. Several other articles reached the same conclusions when examining various climates, including tropical [118]–[123], subtropical [124], and high mountain locations with distinct oxygen conditions [125], as well as regions like Brazil [126] and Chile [127]. Gautam et al. [128] conducted research in 108 traditional houses in Nepal, measuring the indoor thermal environment and conducting thermal comfort surveys across different regions with varying climates. They found significant differences in regional comfort temperatures, primarily attributable to variations in clothing adaptations. Pastore & Andersen [129] conducted a Post Occupancy Evaluation (POE) in Switzerland, highlighting differences in respondents' comfort ratings based on their home climates and time spent in the country and suggesting that in the current comfort debate, the coexistence of people from different origins is undervalued in comfort metrics.

Acclimatization[9], defined as an individual's capacity to adapt to different climates or environments when transitioning from their usual location, has been examined in various studies. Wang et al. [130] investigated the acclimatization of elderly individuals in aged-care homes in Shanghai, concluding that those with longer stays in aged-care homes were more likely to perceive "Neutral" and "Warm" sensations. However, this index did not affect the "Cool" sensation. Nakano et al. [131] studied thermal perception among office workers in Japan, distinguishing between Japanese and non-Japanese workers. They found a significant neutral temperature difference of

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[9] Three different definitions of acclimatization were proposed in 1955: (1) acclimation is an adaptive change (Prosser), (2) acclimation is a demonstrable compensatory change (Bullock), (3) acclimation is any change (Precht), caused by a change in an environmental variable (or variables) in an individual organism and (usually) reversible during its lifetime. [385]

3.1°C between Japanese females and non-Japanese males under their usual working conditions, highlighting the influence of culture and gender. Continued exposure to specific environments and the impact of thermal history on comfort perception have also been explored in various regions of China [132] and among students [133]. Previous life experiences, often shaped by cultural backgrounds, have been observed to influence thermal preferences. People's thermal preferences are also closely linked to their local climate zones and, to some extent, the diffusion of thermal management systems within their respective countries. Yu et al. [134] demonstrated that individuals accustomed to frequent use of air conditioning (AC) might have difficulty adapting to new thermal environments compared to those who prefer natural ventilation. The use of AC systems varies by country, as reported by De Cian et al. [135] who found differing patterns among eight OECD countries. They noted that regions with higher long-term annual average Cooling Degree Days (CDDs), such as Japan, Australia, and Spain, showed greater AC usage due to increasing global temperatures. Beizaee et al. [136] predicted that mechanical AC systems would be more commonly adopted in warmer areas of England, as residents in these regions are less tolerant of low indoor temperatures.

The most employed methodologies for demonstrating the influence of climatic background involve statistical analyses of datasets constructed from questionnaire responses. Based on these methodologies, Pistore et al. [137] propose distinct thermal feeling probability distributions and acceptability rates for various European countries (France, Greece, Portugal, Sweden, UK) and compare them with values outlined in the ANSI/ASHRAE Standard 55. In the summer, Greece significantly differs from other countries, with users showing a lower tendency to favor the "Warm" side of the comfort scale, whereas Sweden exhibits a higher tendency toward the "Warm" range. During the winter, Greece, Sweden, and the United Kingdom display significant differences compared to France and Portugal, resulting in variations among countries regarding acceptability levels associated with standardized indoor conditions.

Geography and environment undoubtedly have an impact, but it's challenging to establish objective parameters, such as latitude, longitude, altitude, or average temperature of a location, because thermal perception is influenced by personal factors (age, cultural background, beliefs, gender, etc.) and different ways of acclimating. The most challenging aspect is, however, distinguishing between physiological adaptation and acclimatization processes, which are closely intertwined and develop differently depending on an individual's upbringings, and non-physiological processes, which are more related to transient emotions or feelings. As Shipworth et al. [138] suggest, a sunny day in a climatic context with a majority of rainy days may lead to different emotions of happiness or joy and a distinctive acceptance of an overheated room, compared to a sunny day in a hot and dry climate.

Appendix A schematically presents the main findings of the research on the topic of "climatic and environmental issues" analyzed in this section. Literature reviews, technical standards, policy articles, ten question papers, and debate papers, although often representing the starting point of the discussion, are excluded from the table, which is limited to reporting field studies, identifying their location, settings, subjects, and results.

Age (n. of paper = 32)

Research conducted as early as the 1960s has highlighted differences in how people of different ages experience thermal comfort [139]. Recent studies have reinforced the notion that as people grow older, they tend to feel colder or hotter more easily due to factors like decreased metabolism, reduced physical activity, and other physiological changes [140]. According to Van Hoof & Hensen [141] and Novieto and Zhang [142], with age, there's a decline in factors like muscle strength, sweating rate, the body's ability to dissipate heat, hydration levels, vascular responsiveness, and cardiovascular stability. This means that older individuals not only struggle more with regulating their body temperature but also have a harder time noticing when it changes. Additionally, they're generally more accepting of changes in their environment [143], [144], which means their thermal comfort needs differ from those of younger people [145].

As highlighted by Spandagos et al. [146] and Yoo et al.[147], biological factors related to individual characteristics like gender, body composition, and age significantly influence an individual's thermal comfort requirements. Shipworth et al. [138] emphasize the importance, among others, of our body as an adaptable system, capable of regulating and controlling its mechanisms to achieve optimal homeostasis based on environmental conditions. This adaptability is strongly influenced by a person's age.

Traditional comfort evaluation models, such as the PMV model or adaptive models, do not account for variations among individual occupants in terms of age, gender, and ethnicity: researchers are so actively seeking new methods to incorporate these parameters into comfort assessments [148]. Zhong & Choi [149] developed an artificial intelligence algorithm trained on occupants' thermal comfort preferences, considering demographic factors, collected during experiments in a controlled environment. Preliminary results from the authors indicate potential energy savings of up to 45% when using HVAC management systems that consider individual occupant characteristics, including age. Additionally, Tardioli et al. [150] introduced an innovative approach based on building physics, Machine Learning (ML), and IoT data to predict indoor thermal comfort in office buildings. They recognized the significance of subjective demographic factors in making accurate comfort predictions.

Concerning age, several studies have explored the role of comfort for more vulnerable population categories, particularly the elderly. The thermal comfort of elderly individuals has received extensive attention in the literature due to its positive impact on the ability of older people to age in place [99]. Moreover, with demographic shifts occurring worldwide, leading to a rapid increase in the number of people aged 65 and over, this research area has become increasingly relevant. Wang et al. [130] presented two data-driven models based on information gathered from over 1000 elderly subjects residing in 19 aged-care homes in Shanghai. They considered 16 parameters, including age, gender, and health conditions, to predict thermal comfort. Tartarini et al. [151] collected subjective perceptions in six Australian nursing homes and correlated them with real-time thermo-hygrometric data obtained through sensor-equipped wheeled walkers. Tsoulou et al. [152] focused on summertime thermal conditions for senior residents in public housing in the USA, with a specific emphasis on heatwaves. According to Mendes et al. (2015), the ability to regulate body temperature tends to decrease with age, potentially explaining why older individuals perceive thermal comfort differently from their younger counterparts. These findings were corroborated by van Hoof et al. [99], who conducted a comprehensive review of the relationship between thermal comfort and population aging. In summary, they reported that older people tend to have different thermal sensations and preferences than younger individuals. This divergence could be attributed to how older people respond to changes in thermal conditions, influenced by factors like different mechanisms for cold and warm defense, metabolic rate, thermoregulatory response, body composition, and cardiovascular flexibility, or even different pathological conditions [138].

The difference in thermal perception across age groups has also been investigated in other studies. Hansen et al. [153] used survey data to explore social differences in comfort conventions and expectations. They found that older individuals tend to prioritize comfort more highly than younger ones, which may result in increased energy consumption. Trebilcock et al. [154] presented results from a field study on thermal comfort in primary school buildings in Chile based on questionnaire responses from 10-year-old students. They found that despite extremely low indoor classroom temperatures during winter occupancy hours and relatively high temperatures in spring, students tended to adapt to this wide variation. Moreover, the comfort temperature for students was significantly lower than that calculated from the adaptive comfort model designed for adults. Regarding temperature preferences, in the early 1970s, Rohles & Johnson [155] observed a distinction among different age groups in the United States. They noted that older individuals tended to prefer temperatures approximately 1°C higher than those favored by middle-aged adults. This preference contrast was also evident when comparing adults to college students. However, in a recent review examining individual differences in thermal comfort [156], it was concluded that despite these variations, elderly and young individuals tend to express similar preferred or neutral temperature preferences. However, it's worth noting that households with older residents may exhibit greater sensitivity to extreme thermal conditions.

Age is also linked to the willingness and ability to utilize tools and devices to modify the surrounding thermal environment. Jian et al. [157] conducted a study investigating the relationship between human body thermal responses and the use of air conditioning among occupants of different ages and genders. Concerning age differences, the study found that elderly occupants exhibited a high degree of thermal sensitivity but greater tolerance compared to young and middle-aged occupants, resulting in less frequent use of AC. The authors attributed this behavior to differences in the behavioral and cultural backgrounds of the occupants. Young individuals had grown accustomed to AC environments from an early age, while the elderly had developed different long-term habits and were more conscious of energy savings. This aspect had previously been highlighted by De Cian et al. [135] in a study on AC and thermal insulation choices for household adaptation in a warming climate. Additionally, they noted that households with children tend to use AC more frequently to enhance comfort for their sons and daughters.

Unlike climatic factors, a quantitative assessment of the effect of age on thermal comfort may appear to be more straightforward. However, in this case as well, age is intertwined with personal factors, not solely linked to the physical changes in the body over the years.

Appendix A schematically presents the main findings of the research on the topic of "age" analyzed in this section. Literature reviews, technical standards, policy articles, ten question papers, and debate papers, although often representing the starting point of the discussion, are excluded from the table, which is limited to reporting field studies, identifying their location, settings, subjects, and results.

Gender (n. of paper = 31)

Several studies highlighted differences in thermal perception between males and females. For instance, Zhang & de Dear [110] discovered that, under identical indoor and outdoor climatic conditions, males tend to perceive the environment as significantly warmer than females in various geographical contexts. Additionally, males exhibit consistently lower thermal sensitivity compared to females [100], [104], [157]. Nakano et al. [131] conducted a survey in Japan, where they observed a neutral temperature difference of 3.1°C between Japanese females and non-Japanese male workers, with females generally perceiving colder conditions. In this study, indoor operative temperature was measured, and thermal sensation votes were collected through questionnaires. The 3.1°C difference represents the variation in average operative temperature values when participants assigned a thermal vote of 0.

While Schweiker et al. [158] explained this variability in thermal perception in terms of physical and biological factors, such as differences in body surface area and clothing types between men and women, other studies have approached gender differences in thermal comfort evaluation from a cultural and social perspective. According to Rupp et al. [159], women tend to prefer warmer environments than men due to physiological variations in their endocrine systems, body compositions, metabolic rates, skin temperatures, and clothing preferences. As also noted by Mazzone & Khosla [81], understanding how gender roles and daily responsibilities are socially constructed can provide insights into how individual behaviors and practices, rather than solely biological differences, can impact thermal comfort. For example, Taki & Alsheglawi [160] focused on the roles of females and males in Islamic culture while developing and testing a framework for energy-efficient housing that aligns with socio-cultural needs in Bahrain. In this case, the influence of gender segregation in society is also reflected in architectural typologies, both public and private, and in the distinct ways in which females and males inhabit these spaces, ultimately affecting thermal preferences.

Hansen [153] found that women generally prioritize home comfort more than men, which can be attributed to the historical gendered construction of the concept of home, where women traditionally have been associated with its private sphere.

Yang et al. [161] analyzed the influence of male and female attitudes on their home energy usage behaviors, including home heating conditions and thermal comfort. They found that in couples or households with more than two occupants, economic factors tend to have a greater influence on heating use than gender differences in comfort perception. This is primarily because one partner's energy behavior often influences the other partner's choices. As previously mentioned, these findings were corroborated by Spandagos et al. [146], who reported that energy consumption choices for heating and cooling are more closely tied to residents' income than sociodemographic differences. However, it does not seem that this gender-related difference in thermal perception translates into different mechanical control of the built environment. Brewer [162] demonstrated that there are no significant differences in thermostat settings between single-occupant females and single-occupant males, even though women are known to experience greater thermal discomfort than men at all temperatures and tend to prefer higher temperatures. The study aimed to address the claim that thermostat standards in shared spaces were designed primarily to meet male thermal comfort preferences. The results, based on research conducted in the United States with a sample of 494 men and 786 women living in single-occupant households, showed that the average temperature setting preferred by females for heating was less than 0.3°C higher than that preferred by males. Furthermore, female preferences were, on average, lower during nighttime in winter because the majority of women reduced thermostat settings before bedtime. While gender does influence thermal perception, control actions appear to be more closely linked to other factors, such as group dynamics. It's worth noting that the study focused solely on single-occupant households, so the reported thermostat-setting choices reflect either male or female preferences exclusively. However, heating set point values were not measured in situ as the research relied only on surveys: subject memory and recall could potentially affect the results.

In the other articles mentioned, a parallel comparison is consistently made between field measurements and questionnaires. Although standard questionnaires defined at the technical norm level (EN ISO 10551:2019 [163] and EN ISO 28802:2012 [164]) are often used, interviews and focus groups with specific and context-dependent questions are frequently required to obtain clearer information on qualitative aspects.

Appendix A schematically presents the main findings of the research on the topic of "gender" analyzed in this section. Literature reviews, technical standards, policy articles, ten question papers, and debate papers, although often representing the starting point of the discussion, are excluded from the table, which is limited to reporting field studies, identifying their location, settings, subjects, and results.

Body Composition and Physical Activities (n. of paper = 17)

The energy cost of a muscular load is measured by metabolic rate, which converts chemical into mechanical and thermal energy, providing a quantitative estimate of a performed activity. The definition of 1 MET (3.5 ml oxygen/kg/min or 4.184 kJ/kg/h, which is roughly equivalent to 58 W/m^2 when the body surface area is 1.8 m^2) was originally derived from the resting O_2 consumption of a 70 kg, 40-year-old man [165], and therefore, as the standards also indicate, corrections may be necessary when dealing with different populations or personal characteristics [166]. Metabolic rate is related to several physiological parameters: body mass and composition [138], age and gender, energy intake and exercise [167] , and diet [168]. All these factors may be related to cultural aspects and habits typical of a given population. For example, according to Poggiogalle et al. [169] the most significant factors influencing food intake can be classified as family structure, housing situation, education level, and income. Diets and related health problems vary greatly among countries [170] although there is little discussion of the types of food and beverages that individuals typically consume to achieve beneficial effects on thermal comfort in various geographical contexts [81]. This would lead to the identification of a cultural matrix of metabolic rate.

Metabolic rate is also related to body composition: several studies, collected in Schweiker et al. [158], evaluate the effect of BMI (Body Mass Index) on thermal perception. Also Rupp et al. [159] demonstrated how men, overweight occupants, and people who are exposed to AC more frequently are more likely than women and non-overweight occupants to express thermal discomfort due to feeling “hot”. According to Abarca-Gómez et al. [171] BMI trends vary globally and are influenced by local economic and cultural factors: in recent years there has been a plateau in average BMI trends in parts of northwestern Europe, high-income English-speaking countries, and the Asia-Pacific region for both males and females. However, in contrast, BMI levels have been increasing at a faster rate in east and south Asia for both genders, as well as in southeast Asia for boys.

Metabolic rate also depends on the activities that people do in their homes or offices. These activities can be related to various socio-cultural aspects, including gender not only as a biological factor but also as a cultural factor. For example, Bahrain's cultural needs impose different lifestyles on women and men, who live in different areas of the home and perform different tasks [160]. It is evident that if the activities that a person performs within an indoor space differ (refer to section "Habits and ways of human-building interaction" to understand how practices often both shape and reflect the cultural fabric of a group or society), his metabolic rate will likewise change, subsequently impacting their thermal sensation. Finally, metabolic rate can also influence thermal perception due to its close association with body, skin, and breath temperatures, as well as with a person's age and gender [172]. This connection is typically explored in the literature by investigating oxygen consumption [173] and carbon dioxide production [174] during exercise and recovery periods, relying on the principles of indirect calorimetry. The results differ from individual to individual and within particular age and gender groups.

Although technical standards (EN ISO 8996:2022 [175]) list more accurate calculation methodologies, most thermal perception studies have applied easy-to-use and low-cost methods, such as activity diaries and heart rate monitors [158], disregarding the socio-demographic factors listed above.

Appendix A schematically presents the main findings of the research on the topic of " body composition and physical activities " analyzed in this section. Literature reviews, technical standards, policy articles, ten question papers, and debate papers, although often representing the starting point of the discussion, are excluded from the table, which is limited to reporting field studies, identifying their location, settings, subjects, and results.

Clothing level (n. of paper = 21)

Clothing has a clear impact on a person's thermal equilibrium in neutral, cold, and hot situations: knowing its thermal properties, such as thermal insulation and water vapor resistance, is therefore mandatory to assess the thermal stress of humans in cold, neutral, and hot environments. Despite its fundamental role in estimating thermal comfort, there are, however, some limitations in assessing clothing insulation values of traditional dress patterns, still widely used worldwide, which are not mentioned in the clothing database of the

ASHRAE 55 and ISO 7730 standards. For instance, with reference to the Arabic culture, Farghal & Wagner [176] underlined the lack of parameters for veil, “abaya” – a traditional silk or wool loose cloak – and flip-flop slippers – used by Egyptian males also in winter – in the database of the standard ISO 9920 [177]. Singh et al. [178] reported that a lack of proper characterization of clothing level is critical in analyses conducted in South Asian countries, particularly India, where people predominantly wear traditional clothes, both at home and in the office. They considered in their analysis specific clothing insulation values of traditional attire, such as sari and salwar-kamez, calculated in previous studies. Gao et al. [179] conducted a manikin experiment to investigate whether convective and radiative heat transfer coefficients vary with different clothing ensembles. They examined eight sets of clothing, all of which, however, closely resembled typical Western winter attire. Despite the similarities, the study revealed a significant variation in convective heat transfer coefficients, with the largest difference being 32%. According to Tabaie et al. [180], even the assumption of uniform clothing coverage can lead to misleading conclusions, with an average deviation in thermal sensation ranging from 0.2 to 0.45 units when wearing clothing suitable for the hot season. Considering that different countries have unique dress practices rooted in their cultural, historical, and social contexts [181], it becomes evident that a more thorough quantitative characterization of the clothing's contribution to thermal comfort is necessary, especially when comparing data collected in different social settings.

Considering traditional clothing can also help uncover the true mean comfort and preferred temperature of local residents. For example, Gautam et al. [128] found that a significant regional difference in comfort temperature exists in traditional houses in Nepal due to different clothing adjustments: the mean comfort temperature in the cold region was 13.8°C, which is 4.1°C and 9.3°C lower than that in temperate and subtropical regions, and it is significantly lower than that given in ASHRAE and CEN standards. The results, however, have limitations as there is a lack of data on insulation levels for traditional Nepalese clothing. Therefore, the authors had to rely on the nearest available insulation values from the CEN standard and similar research studies.

The influence of clothing on perceived comfort is, in fact, not much investigated in the literature given the ease with which clothing can be removed or changed. Changing clothing insulation is the most immediate adaptation for thermal comfort adjustment but it is very difficult its continuous monitoring as well as ensuring through questionnaires the exact correspondence between what the interviewer says and the precisely worn dress. The most commonly used methodology is to compare the clothing level recorded in a questionnaire with other environmental variables to identify the best clothing behavior [130]. However, this type of analysis tends to associate clothing with a numerical level, overlooking the cultural traditions that underlie one's clothing choices, especially in indoor environments.

Appendix A schematically presents the main findings of the research on the topic of "clothing level" analyzed in this section. Literature reviews, technical standards, policy articles, ten question papers, and debate papers, although often representing the starting point of the discussion, are excluded from the table, which is limited to reporting field studies, identifying their location, settings, subjects, and results.

Habits and ways of human-building interaction (n. of paper = 44)

Just as all methods of control and interaction with the building can have an impact on thermal comfort, the adaptive behavior of building occupants can also be crucial in changing the thermal sensation. Research agrees that, although occupants' behavior is still difficult to quantify through parameters or numerical models, it is one of the main drivers of variance in assessing building energy and comfort performance [182]. The actions under behavioral adaptation can include wearing light clothing, eating in open spaces in the summer, avoiding direct sunlight, sleeping under a blanket in the winter, taking cold showers, opening or closing windows, using fans at various speeds and times, choosing a cool place to sleep, drinking cold water, etc. [183]. Socio-cultural factors, local climatic conditions or resource availability may influence any of these decisions, as well as human-building interaction, which is often the result of practical experience gained in the specific space and context in which one lives.

Singh et al. [115] carried out an adaptation analysis to know the processes by which some subjects in Indian offices take action to restore comfort. Results show that the personal adaptation of subjects in the offices in Tezpur and Shillong – two cities in different climatic zones of India – is quite different during the autumn season. While in Tezpur primarily rinse face/hands, drink hot/cold beverages, avoid sunlight, and move to airy places, subjects in Shillong move to warm places, avoid airy places, drink hot/cold beverages, and add clothing. Thapa et al. [184] also deepened the variation in thermal sensation, thermal preference, clothing insulation, neutral temperatures and other behavioral adaptive measures undertaken by some subjects in

Darjeeling, India, such as hot and cold drink intake and number of showers to feel comfortable. To obtain such qualitative data, respondents were assisted in completing the questionnaire, and a list of thermal regulation measures to choose from was presented in advance. In contrast, Takasu et al. [185] noted that the adaptive behavior of some Japanese workers to adjust comfort conditions consisted primarily of flexible clothing and window-opening for natural ventilation. In this case, the questionnaire was very specific about the level of clothing but to record the use of environmental controls in the office, use of heating, cooling and electric fan and the proportion of open windows the researchers were required to note these personally and this could have a negative impact on the validity of the results. Tsoulou et al. [152] highlighted the substantial impact of actions like opening windows and using air conditioning in certain low-income senior apartments. The study showed that the adaptive responses of seniors vary significantly across sites with different outdoor amenities and building envelopes. Some residents rely on central air conditioning, while others employ a broader spectrum of adaptive measures, sometimes achieving comparable indoor thermal comfort indices. However, only actions that are easily monitorable remotely with sensors or questionnaires fall within this spectrum, such as the opening of doors and windows and the level of clothing. Based on field measurements for 54 occupants in 35 apartments in Beijing over one summer, Jian et al. [157] analyzed the AC switch-on behavior to reveal the nature of occupants' tolerance of thermal discomfort before turning on AC in summer. They found that the human body's tolerance of hot indoor environments is more affected by psychological conditions and behavioral and cultural backgrounds than by the physiological conditions of age and gender. This conclusion is still a speculation by the authors, relying on their knowledge of the analyzed context rather than on quantitative evidence. In all these works, in fact, adaptive behaviors are not interpreted as cultural patterns and it is difficult to identify connections between them.

Some other papers identified links between people's lifestyles and thermal comfort more from a qualitative point of view. Most of them focused on vernacular and traditional architecture, also highlighting the interrelation between space/construction typologies and residents' habits. For instance, the comfort conditions in Japanese traditional houses in hot and humid climates are actively sought by the inhabitants. These conditions are guaranteed in winter by the use of thick cloths and small objects to heat the body locally and, in summer, by the operation of large surface of paper panels and the connection with the outside nature through the veranda [186]. In the

Mediterranean climate, some examples come from the vernacular Cypriot farmhouses where the inhabitants, as a result of accumulated knowledge and practical experience, constantly and intuitively apply passive heating and cooling strategies rooted in tradition [187]. Another study explained the lifestyle of Tibetan residents in terms of thermal adaptation; in winter, they wear thick clothes and drink butter tea to protect themselves from the cold at home, while in summer, they wear less thick clothes and regulate the thermal environment by using shade and open windows [188]. In this case as well, understanding the context of the case studies is crucial, and all this information is based on previous knowledge rather than on-site monitoring.

A significant work was provided by Varolgunes [189], who evaluated indoor comfort conditions in both vernacular and new housing in a cold region of Turkey. A survey was conducted with 100 participants, consisting of 50 living in traditional houses and 50 in modern houses. The questionnaire covered demographic information, heating habits, space usage, and preferences for heating, cooling, and ventilation. It also assessed satisfaction with thermal and visual aspects, usage areas, and overall building design. However, thermal comfort was evaluated using only basic questions. The author found that vernacular houses, based on passive design strategies, were energy efficient and well suited to occupants' thermal requirements in the past since their behavior and lifestyle was "calibrated" to the traditional architecture conformation. However, these habits are rapidly disappearing in new buildings partly because the traditional lifestyle is also disappearing. Both Varolgunes [189] and Sdei [186] stated that vernacular architecture could give important lessons for designing new buildings with a bioclimatic approach suited to occupants' needs. This was clear also to Williamson et al. [190] who analyzed the comfort and energy use of five Australian award-winning houses, concluding that this inefficiency was related to the regulatory concept of "meeting generic needs" that failed to account for the diversity of socio-cultural understandings, the inhabitants' expectations, and their behaviors. Nevertheless, even today, comfort standards continue to ignore these factors. Recently, Costa-Carrapiço et al. [191] highlighted this inability to assess comfort correctly; applying the Portuguese context-adopted Thermal Comfort model (PTC) to vernacular architecture, they found that occupants of traditional buildings have a wider thermal tolerance if compared with ranges of national and international legislation and those of contemporary dwellings. Gram-Hanssen [192] provided a detailed analysis of empirical evidence from different households living in similar buildings in a suburb of Copenhagen, Denmark, showing significant variation in energy consumption due to different usage patterns of both the house and its heating system. The author found that technologies, embodied habits, knowledge, and meanings are the main components in the understanding of their practice. Regarding embodied habits, some of the interviewed households explain their behavior in regulating their indoor climate recalling their experience of other practices e.g., habits in the workplace or parents' habits in their childhood experience.

Few studies investigated the occupants' spatial behavior in domestic spaces as an adaptive behavior in socio-cultural terms. For example, Ibrahim et al. [193] collected information from occupants of 35 apartments from a residential compound in Ammam, where the apartments are generally divided into four zones: Private, Semi-private, Public (significant spaces in the Jordanian culture normally used for hosting guests) and Outdoor. The most influencing variables on occupants' spatial behavior were their thermal satisfaction and performed activity, but also other factors such as occupants' age, outdoor temperature, parents' educational level and the availability of AC units. The importance of having multiple thermal zones within an apartment and how they are used throughout the year in Iran is also emphasized by Foruzanmehr [194]. During the summer, for instance, occupants are used to sleep on the roof and during the daytime, they moved between the courtyard, the summer quarters, and the basement, depending on the outdoor temperature.

Over time, habits have changed, as have the ways in which people interact with the building and the heating system: the interesting study by Sahakian et al. [195] shows how heating set-point temperatures in Switzerland have changed over the past century, and how solutions once used to get warm (sharing a bed, sleeping in clothes) are no longer common. Today people are used to walking around the house barefoot and in t-shirts even in winter, regardless of outdoor weather conditions.

The importation of Modern design and Western style in hot climates caused thermal discomfort because local and cultural factors were not considered. In Ghadames (Libya) the traditional architecture determined a compact urban structure through a peculiar house composition; three levels with full-shaded rooms on the ground floor and exposed spaces on the top floor (e.g., kitchen) with small courts that ensure natural ventilation. Households are satisfied with old buildings thanks to the architectural layout, construction materials, indoor comfort, and energy consumption because they fully reflect the local culture. Moreover, they adopt specific behaviors to face extreme conditions, for instance, they use different inner spaces in relation to the season. Quite the opposite, the layout of the modern building is developed in one or two levels without full-shaded rooms and is distinguished by larger external openings; so, it requires artificial systems to achieve thermal comfort [196].

Vernacular architecture does not always guarantee better comfort conditions than Modern one; nevertheless, some householders are not ready to accept any compromise to reach it. Djafri et al. [197] undertook a study on traditional housing in Algeria proposing actions to enhance building thermal behavior. Most householders refused invasive interventions such as reorganizing openings and improving physical parameters with new materials because their connection with the house could have changed: «old houses are their traditional houses and owned by their family in generations and the design or layout of the houses tend to promote family relationship and intimacy among the occupiers».

In all the presented studies the methodology is consistently similar and relies on questionnaires and interviews combined with real-time monitoring of environmental parameters, which are then compared with thermal votes. There is no defined list or checklist of activities or habits to check, and many of the correlations between thermal comfort and ways of living in an indoor space are more the result of prior knowledge of the context, sociological investigations, and interviews, not fully supported by quantitative data. However, it is evident that indoor thermal comfort is closely linked to building components, systems, and the overall quality of the living environment, as well as how people interact with it. The physical, technical, and financial feasibility of modifying these aspects undoubtedly offers potential benefits to end-users and influence their thermal expectations. As documented in studies by Horne & Segura [198] and Yun [79], the mere perception of having control over these elements enhances occupant satisfaction with thermal conditions.

Appendix A schematically presents the main findings of the research on the topic of " habits and ways of human-building interaction " analyzed in this section. Literature reviews, technical standards, policy articles, ten question papers, and debate papers, although often representing the starting point of the discussion, are excluded from the table, which is limited to reporting field studies, identifying their location, settings, subjects, and results.

Contextual factors (n. of paper = 23) & Socio-physiological aspects (n. of paper = 17)

The perception of thermal comfort and the requirements for heating and cooling can also be influenced by contextual factors and cultural beliefs [81].

As suggested by Shove [199] and Humphreys [200], norms and standards have evolved to promote a "one size fits all" approach to comfort, where if most buildings are heated to a specific temperature, that temperature becomes the norm. Many commercial, advertising, economic, and social factors are built upon this standard, encouraging people to conform to guidelines established by engineers, economists, and planners [81]. Our behavior is significantly influenced by the customs of a neighborhood or school, which even unintentionally define both the possibilities and restrictions in conducting one's life in those environments. Similarly, the practical traditions of a specific society or profession play a role in determining acceptable behaviors and restrictions on individual actions [201]. Although knowledge and information on how to manage a thermal environment are transferred across generations, according to Van de Vliert [202] «the circumstances in which societies adapt their cultural values and practices to cold, temperate and hot climates include the availability of funds to cope with climate». Political choices, energy efficiency strategies and architectural design standards in richer countries or in those with more demanding climates, have led to considering energy efficiency in buildings and indoor comfort as a right, thus leading to a relatively high quality of the housing stock. However, this did not occur for historically poorer countries, causing evident differences in the heating and cooling needs of users and in the way they tend to adapt to thermal environments [198]. Hargreaves & Middlemiss [103] point to three main social relationships that could interfere with the way people live and consume energy inside buildings: relations with family and friends, with agencies and communities and those associated with social identities. While these relationships may be based on sharing definite body types, social statuses, or family structures, they are also reflected in policy and practice – affecting access to state support – and contribute to the development of energy-consuming behaviors. In this regard, Pacheco & Lamberts [126] wonder: if energy standards and policies designed for Western countries continue to be applied tout court in every nation, how the culture and history of these countries influence the adoption of HVAC systems and super-insulated walls, even when not strictly necessary?

According to Chappells & Shove [203], the use of AC for mechanical control of indoor temperature is widespread all over the world independently of real needs or climatic conditions. Nevertheless, the designers and practitioners they interviewed underlined an interesting countertrend phenomenon: a cultural factor that is changing - and will be able to change - the way to conceive thermal comfort is the sensitivity towards environmental sustainability because some people are willing to accept compromises in the name of reducing the impact on the environment.

Over the years, environmental concerns have grown significantly. An intriguing finding from Cui et al.'s [204] study on factors influencing heating behavioral patterns in China is that environmental awareness ranked as the second most influential factor shaping residents' behavior. It followed thermal comfort preferences as the primary driver and was followed by considerations of economic resources and energy habits. The results were obtained by conducting interviews with 904 individuals, who were presented with a three-page questionnaire. This questionnaire aimed to collect information in four distinct categories: demographic details (such as age, education, occupation, and income), attributes of the building (including its type and year of construction), patterns of heating behavior (both current practices and future intentions regarding heating), and the underlying motivations influencing the choice of a specific heating pattern (economic factor, environmental concern, thermal comfort, energy habits).

De Cian et al. [135] asserted that households with a strong focus on sustainability tend to prioritize thermal insulation over air conditioning systems, as the latter can lead to increased energy consumption. These conclusions were obtained by analyzing historical data from the 2011 Environmental Policy and Individual Behavior Change (EPIC) dataset.

Regarding socio-psychological aspects, building science frequently measures comfort using equations that only depend on environmental and individual physical characteristics parameters that can be measured objectively. Although comfort is a mental experience, models for evaluating it typically avoid “the mind” by making it a more tangible and objective category [49]. Considering occupants not only as individuals but also as members of social groups can be important to deepen the knowledge on the socially constructed thermal comfort perception. Indeed, people often mirror each other’s behavior towards group integration and identification [205]. In this way, the creation of a new need is fundamentally influenced by peer emulations, as Mazzone & Khosla [81] explain in relation to the diffusion of the AC. This concept is well analyzed by Healey & Webster-Mannison [206] focusing on the main factors that influence thermal comfort in office spaces. Here, occupants, as members of a social group, make group decisions about comfort. The semi-structured interviews they conducted in a pilot small professional office revealed that people may be reluctant to impose their preferences on others, particularly in large work groups. Hargreaves & Middlemiss [103], citing other interview-based research, emphasized how much the energy behavior of users within a building and the resulting comfort preferences are a trade-off between different sensitivities: the needs and presence of children, pets and plants, the household characteristics, the different skills and attitudes of those who operate the thermostat or open windows, and discussions with neighbors are all variables that influence the ultimate perception of comfort. Gender, generational, and classified expectations also affect levels and patterns of energy demand and consequently preferred levels of thermal comfort. People's willingness to conform to social expectations or to see themselves as different from others (social status) has an important impact on how they behave in buildings [207]: differences have also been identified between immigrants and native-born individuals, especially in relation to environmental awareness.

All the mentioned studies are based on conclusions drawn by researchers from interviews, often with open-ended questions, and very different questionnaires. There is no well-defined analytical framework in the literature that systematically allows for the consideration of such qualitative aspects in the assessment of indoor comfort. The few statistical models used for analyzing questionnaire responses are difficult to adapt to other research based on different questions. In many cases, the approach and focus are more sociological in nature, and only in one article [203] the topic is addressed from the perspective of stakeholders of the built environment.

Appendix A schematically presents the main findings of the research on the topic of " contextual factors and socio-physiological aspects " analyzed in this section. Literature reviews, technical standards, policy articles, ten question papers, and debate papers, although often representing the starting point of the discussion, are excluded from the table, which is limited to reporting field studies, identifying their location, settings, subjects, and results.

Income and education level (n. of paper = 27)

Thermal comfort in low-income housing often involves a trade-off between comfort and socio-economic-cultural factors. Indraganti & Rao [208] examined the thermal comfort of residents in various apartments in India. They observed that individuals in the lowest economic bracket exhibited a greater tolerance for elevated indoor temperatures. This tolerance was often a result of their limited or nonexistent access to air conditioning, leading them to rely on strategies like cross ventilation and behavioral adaptations, such as taking hot midday siestas. Likewise, low-income residents of certain traditional homes in Bingol, Turkey, reported in surveys that they cope with the cold conditions in their region by employing passive strategies instead of relying on HVAC systems [189].

Tsoulou et al. [152] observed that, besides apartment characteristics, occupant behaviors have a significant effect on indoor thermal performance and that those behaviors vary significantly based on the resources available to residents. The results of the analysis showed that occupants who live in air-conditioned apartments overall enjoy thermal comfort index ranges that fall within the ASHRAE standards, differently from those who did not have access to AC. Petrova et al. [209] conducted interviews with 3000 individuals, and their findings suggest that the factors most significantly influencing indoor thermal comfort are material-related, such as the energy efficiency of the house and financial constraints, rather than sociodemographic factors like age or gender. Each interview, lasting approximately one hour, encompassed around 100 diverse questions, contributing to a final dataset comprising over 300 variables. The cost of energy and the feasibility of implementing building retrofit measures are the determining variables, according to Schweiker et al. [158] review.

In order to pay their expenses, people who experience fuel poverty must spend less on a variety of necessary goods and services. Ortiz et al. [210] compare how people with low incomes and those with no financial constraints perceive winter thermal comfort. The findings of their surveys and monitoring reveal a clear distinction between the groups, with those who experience energy poverty reporting worse thermal conditions at home. The emotional strain of living in poverty – worries about energy bills or debt and the lack of any solutions or a sense of control over the problem – and the close correlation between energy poverty and that load may also be contributing to this unhappiness. According to the authors, the fact that 86% of people in fuel poverty spend most of their time at home as opposed to only 46% of households not in fuel poverty is another factor that could affect how thermal comfort is perceived.

In some cases, the gap produced by different incomes in adapting to thermal conditions is evident also in public buildings. The findings of Trebilcock et al.[154] show a high correlation between 440 students' comfort temperature in winter and the IVE-SINAE index (a social vulnerability index), thereby suggesting that children that come from deprived environments tend to adapt to lower temperatures better than those who come from less deprived ones.

This may relate back to fuel poverty at home that forces children to adapt to harsh thermal conditions, and therefore, expect lower temperatures at school.

Referring to the preference of households between AC and thermal insulation to adapt to a warming climate, De Cian et al. [135] highlighted a worrying trend that could increase energy consumption in the future, with negative effects on the environment: rising income levels in emerging economies in warmer areas of the world could lead people to preferentially choose AC systems, which are rather cheap and have short- to medium-term benefits.

In their study carried out in Chile, a country with a relevant economic discrepancy between citizens, Becerra et al. [211], involving and monitoring 20 households distributed in 5 socioeconomically disparate communes, found that life quality disparity influences thermal discomfort. A low income induces the choice of the cheapest heating sources, responsible for a higher level of air contamination of indoor spaces that compromises the overall living comfort. As also emerged in Austria, poverty can discourage retrofitting actions because this class of inhabitants cannot face the rent increase, unavoidable to recover costs, also because their energy consumption for achieving thermal comfort before renovation is usually the minimum [212]. Healy & Clinch [213], comparing data from previous surveys on the housing stock in Ireland, investigated whether and which energy-saving measures have been implemented, how often the respondents were unable to adequately heat their homes, family composition and the number of occupants, marital status and the number of dependent children, whether the dwelling was close or far from the city center and services, levels of educational attainment, dwelling age, employment status, and the main source of income. For those who lack such energy-saving measures (insulation, draught stripping, double glazing, etc.), the authors inquired why they do not invest in retrofitting their homes. 31.6% cited financial constraints as the reason, but it's worth noting that 32.3% mentioned that they were unaware of the benefits of these measures. This result has clear implications for policy makers.

Appendix A schematically presents the main findings of the research on the topic of "income and education level" analyzed in this section. Literature reviews, technical standards, policy articles, ten question papers, and debate papers, although often representing the starting point of the discussion, are excluded from the table, which is limited to reporting field studies, identifying their location, settings, subjects, and results.

Language (n. of paper = 13)

Finally, also language is a cultural factor to be considered in thermal comfort evaluations. Many studies [214] explain that ASHRAE thermal sensation scale should be used with caution when translated to other languages for questionnaire-based thermal comfort surveys because the outcome is influenced by interpretation in that language. Indeed, the way individuals explain and assign meaning to thermal phenomena might be influenced by the way language and the vocabulary on thermal sensations are developed in different geographic areas [215]. This result was found in different areas. In Japan, Takasu et al. [185] paid attention to the translation of the questionnaires to assess the thermal comfort of adult workers in office buildings. A similar problem was illustrated by Trebilcock et al. [154] for submitting questionnaires to 10-year-old children in Chile. Moreover, it is believed that correct translations, also adapted to a local context, can encourage users' participation in surveys and contribute to more accurate outcomes [105], [216], [217]. For the Arabic language, some studies addressed the problem of translating questionnaires from English. Farghal & Wagner [176] adopted the ASHRAE scale to evaluate indoor comfort in Egyptian educational buildings. They changed the denominations of the highest point and of the lowest one (3=hot and -3=cold) because the words "hot" and "cold" cannot be translated into Arabic. For this reason, "3=hot" was replaced with an expression which means "very warm" and "-3=cold" with "very cool". However, regarding the adjective "warm", Al-Khatri & Gadi [216] highlighted that its literal translation can be understood as "a desirable sensation especially in winter"; so, they suggested using an expression similar to the English meaning of "hot" in order to underline a negative acceptation of the sensation to which they referred. As a consequence, the changes for the Arabic version of ASHRAE scale are +2=hot (not warm) and +3= very hot (not hot). In this way, the thermal range, even if formally different from the English one, considers the adaptation to local culture.

Similar difficulties in the translation of English scales also emerged in translations into French, Swedish, Portuguese, Greek, and Japanese languages [218], [219]. Chen et al. [220] translated the English questionnaire into Chinese, French, German, Italian, Polish, and Portuguese developing and adopting a translation guideline protocol to avoid any deviation.

Simplicity and clarity of questions is a key factor in the design of comfort-related questionnaires, as illustrated in the interesting work of Montazami et al. [133] conducted to better understand the thermal comfort perceptions of

662 students aged between 8 and 11 years old. Children's motivation is critical to the reliability of questionnaire responses and the use of pictures and colors can be an effective tool in this regard. As suggested by Rodriguez et al. [121] the collection of comfort data requires, in fact, tools tailored to occupants of different ages.

2.5 Discussion and outcomes

This review study attempts to thoroughly analyze the socio-cultural aspects that affect how different groups perceive thermal comfort. The outcomes, reported before, describe the current state of research and forecast future developments in comfort understanding and design in multicultural contexts. To respond to the suggested research questions (see Section 2.1), this section opens a discussion and offers critical insights into how designers might consider these various viewpoints.

As results demonstrated, there is growing attention to aspects influencing the perception of indoor thermal comfort within a given social community beyond conventional physical and environmental variables. Even the more objective factors (such as gender, age, and climate) can be seen from a different point of view if the cultural aspects are taken into consideration. Among the whole spectrum of actions a person can perform to thermally adapt to the environment, from opening windows to wearing extra clothing, it is easy to find habits linked to culture. These are often the result of an underlying history, closely linked to the architecture and spaces that have shaped our lives for much of the time we have lived in them. How we relate to these spaces has generated approaches, preferences and experiences that are reflected in our daily choices and the reasons why we prefer, not merely thermally, one place to another. Behavior, interactions with the building, and actions taken to enhance indoor thermal comfort, often the primary cause of excessive energy consumption, are formed based on past experience and the lessons of tradition, which differ from country to country, but also within the same country. Over time, habits and needs can and have changed to some extent. For those designing a building that will last for decades or interventions of energy retrofitting on existing buildings, it is often not easy to understand what a passing trend is and whether a new habit is likely to last. It also happens that homeowners, even though most new buildings can be widely considered more efficient and comfortable, often are not ready to change their homes and are reluctant to accept invasive changes of the interior layout.

Depending on the context, people are subject to regulations and social constraints that influence the way they manage and perceive thermal comfort in their homes, from managing the set-point temperature of our heating system to buying an air conditioner to withstand the high temperatures in hot seasons. There are diverse materialistic interactions with buildings based on sensitivity to environmental issues and perceptions of the impact of "thermal choices." Indeed, behaviors often emulate those of others, influencing both daily life and project approaches, leading to the importation of design solutions from other climatic and cultural contexts that are not universally applicable. The family's financial situation is also significant, as residents will be more or less tolerant of challenges caused by external circumstances, such as the inability to find affordable housing, pay for an air conditioner, or cover heating costs. Moreover, a low-income family is likely to spend more time at home, statistically increasing their awareness of possible problems and discomforts.

Even if the research has selected a wide range of studies to discuss socio-cultural factors influencing thermal comfort perception and has reviewed them systematically, no structured model for evaluating socio-cultural factors influencing indoor thermal comfort has been identified. The closest attempt to create an analytical model is by Liu et al. [221], who use weighting factors calculated using the Analytic Hierarchy Process (AHP) method to differently weigh types of adaptation to the thermal environment (physiological, behavioral, psychological), taking qualitative aspects into account. They provide a list of parameters to monitor or assess through questionnaires, including skin temperature, heart rate, sweat, pulse rate, health status, air velocity, temperature, relative humidity, clothing and activity level, variability and availability of environmental controls, perceived control level, previous thermal experience, and building context. The weighted sum of all these parameters would allow for a more comprehensive assessment of thermal comfort. However, it is still unclear how to collect these data using a repeatable methodology, and it seems impossible to avoid post-occupancy evaluations and interviews tailored to the specific case study. The model is also based on a very small pilot study and requires further validation. An interesting model for both qualitative and quantitative assessments is the Atlas of Comfort [97], presented in Section 2. However, the model does not allow for the comparison of different groups of individuals but is more a collection of personal and individual factors. It is the author himself who states that it is not advisable to gather all individuals into the same group: "*The recommendation is to group individuals who, due to non-physical personal factors, are expected to share similar satisfaction functions (e.g., people whose family composition is similar)*".

In all the other cited studies, there is a consistent list of variables that are analyzed to assess thermal comfort and they do not deviate from what is already reported in the regulatory standards (ASHRAE and CEN standards). However, when the interest shifts to analyzing more qualitative factors, the solutions remain to either customize the questionnaire or switch to interviews and focus groups based on the researchers' prior knowledge of the context where the study is conducted. To do this, often each of the aspects listed in this review (climatic and environmental issues, demographic factors, metabolic rate and clothing, habits and ways of human-building interaction, contextual factors, income and education level, socio-physiological aspects, language) is addressed individually or in groups of 2 or 3 aspects. There is never a more holistic view of the topic. A second approach is the analysis of large databases through, for example, machine learning procedures [149], [150], to find correlations between thermal sensation and specific clusters (people of the same age, gender, with the same thermal history, etc.). However, these databases do not always contain information about the culture and beliefs of the people who participated in the surveys, and there is a risk of generalizing results based on simple statistical indices.

The presented study is affected by some limitations. This systematic review has been conducted scanning the two major databases and then supplementing the search with a snowballing technique. The primary sources were journal articles, conference papers, reviews, and book chapters. This method introduced a bias because other sources were not considered, which constrained the amount of actual and applied case studies that could be examined. Moreover, it is important to call attention to some trends. The geographical region from which papers most frequently originate is Asia. In contrast, some regions are not taken into consideration due to a lack of research material on the topic. Additionally, the study examined cases from various building functions (often offices and residences), where social norms and interactions with other people might sometimes change how someone behaves when faced with discomfort. The analysis is conducted through the search queries shown in Table 2.1: future studies will need to broaden the sample of analysis by, for instance, extending the search parameters and using other databases, project reports, or other sorts of documentation from the non-academic world (for instance public institutions and statistics centers)

Further research is needed to bridge the gap between thermal comfort models and the more complex and subjective reality. Increasing knowledge in this direction would also greatly benefit the design field towards a more comfortable and sustainable built environment. The assessment of indoor environmental quality in the present standards should be reviewed, as Luo et al. [166] proposed, as their strict criteria could not always accurately reflect genuine thermal comfort. Indeed, realizing what is important to design for reaching indoor thermal comfort conditions is not easy either for the designer or often for the occupant, who struggles to define in a universally valid lexicon and scale of values his or her personal feelings and perceptions on a topic of such a subjective nature. Compliance with the standards requirements is not the only way to pursue and, in addition to subjective factors, it is necessary to make assessments on the influence of socio-cultural aspects.

The most realistic solution remains to design for flexibility, to ensure the ability to adapt to the environment not only through actions but also with and through changing building components that can be easily modified and adapted to different needs. However, the commitment of the designers alone is not enough. Users should be aware of issues related to thermal comfort: this can derive from different factors of socio-cultural nature among them educational attainment, lifestyle, sensitivity to sustainable topics, in addition to lived experiences. Flexibility can thus be combined with participation means, bringing together different people living in the same community, including them through the design of appropriate spaces for all. In communities that are becoming more and more hectic and multicultural, disconnections are evident even within many families, with the elderly and the young hardly able to share moments and activities, and yet unable to carry on those intuitively and passively sustainable teachings and ways of living that were predominant in the past. Therefore, designing for an "average user" is, in most cases, an acceptable compromise, but when such marked discrepancies and users with opposing behaviors, needs, and cultural backgrounds come into play, it is necessary to review the principles underlying the design of living spaces. More flexible approaches and new comfort strategies should be encouraged.

2.6 Concluding remarks

Addressing the intricate interplay of comfort and energy consumption within residential contexts necessitates a holistic approach that encompasses not only the tangible, physics-based aspects of the indoor environment but also the intangible, subjective dimensions of human experience. Looking forward, fostering a convergence between technical studies and the social sciences emerges as a highly desirable goal.

A home serves as a place offering residents control over their immediate environment, enabling them to engage in activities without being influenced by external stressors or uncontrollable circumstances: the notion of comfort thus encompasses a deeper sense of freedom, particularly within the confines of one's own dwelling. In the context of residential living, also energy assumes a more personal dimension, often linked to the financial aspect, represented by utility bills. Efficiently managing and optimizing energy usage involves finding a balance that involves raising awareness and encouraging judicious consumption patterns, all while safeguarding the paramount aspect of comfort (see Section 4.3.1).

Designing within environments where emotions, expected outcomes, beliefs, and even cultural factors intertwine is still, however, a multifaceted challenge.

3 MEASURE COMFORT AND ENERGY USE IN THE BUILT ENVIRONMENT

> *"People are often the best measuring instruments, they are just harder to calibrate."*
>
> PROFESSOR G. RAW

3.1 Background and aim

Once the definition of comfort and energy in residential environments has been clarified, it is necessary to understand how to measure and define them quantitatively. On-site monitoring of comfort and energy is crucial, as the literature has demonstrated [222], [223], highlighting, under the term "performance gap"[224], the significant disparity between what is expected during the design phase and the actual performance of the building during operation. While monitoring energy consumption is intuitively more straightforward, both consumption and production side, as we learned in Chapter 2, the comfort of an occupant within a building is complex and comprises multiple factors: physical well-being, mental well-being, and a sense of freedom and control over the environment. As reported by Lassen and Goia [85], in order to measure comfort, considering its subjective nature, in addition to the basic knowledge of the user's location and activities and the building's features (see [225] for further details), it is necessary to consider multiple levels of interaction between humans and the indoor space. It starts with sensation, the first contact through the five senses with the surroundings, followed by perception, the neural process of translating sensation, cognition, which involves conscious or unconscious reasoning about what is perceived, and finally satisfaction. All of this is influenced by the user's expectations and the set of socio-cultural values described extensively in the previous chapter.

With the specific aim of providing a reference for those intending to monitor comfort and energy in residential environments or for those, as described in Chapter 5, planning to build a monitoring system from scratch, Section 3.3 presents, in tabular form, the most important physical-environmental monitoring parameters mentioned in the literature and used in practice. It also indicates the thresholds defined by laws, standards, and design protocols. The section also discusses the Post-Occupancy Evaluation (POE) methodologies, typically used to assess issues that are not strictly physical, physiological or environmental. Moving from the variables to be measured to the tools for measuring them, Section 3.4 introduces new IoT and smart home technologies, describing how these tools differ from traditional monitoring systems, and then discussing if, how, and when they can replace them in a more user-centered approach. Related discussion also arises from field experience gained in energy-environmental monitoring projects with more conventional systems. Section 3.5, therefore, through a real case study, highlights the technical challenges in the field implementation of an environmental monitoring system, with particular attention to data management, validity, and communication. The knowledge of these issues formed the basis for developing the alternative solution presented in Chapter 5.

3.2 Methods

For the tables presented in Section 3.3, the references are European and American standards, CEN and ASHRAE, in addition to the recommendations from widely adopted building certification protocols (Well, Leed, Breeam, Living Building Challenge). National non-mandatory standards and other recommendations have been excluded to provide a framework as universal as possible and to prioritize those monitoring parameters most requested in professional and work practice. The aim is to define references for a flexible monitoring system that can simultaneously meet the requirements defined by standards and allow for a broader and less directed exploration typical of academic research. Another useful reference in this regard has been the documents produced by various IEA Annexes, the series of subprograms or collaborative research projects managed by the International Energy Agency in collaboration with its member states. Annexes 66, 69, 71, 79, 87, and 81 provided valuable support, with various insights derived from participation and discussions at meetings organized by the agency and open to various researchers and stakeholders, specifically those of Annex 79. Section 3.4, more discursive in nature, revisits the concept of data as information useful for the end-user and not just for the researcher, and provides a description of the context in which the monitoring and automation system developed and described in Chapter 5 is subsequently developed. Section 3.5, instead, refers to the Renew-wall research project, one of the side-projects, along with Dhomo, IsolMAX and ARV project, followed during the doctoral journey. The main objective of the project was the development of prefabricated modular wooden walls for the retrofit of existing condominiums, an ETA system tested in laboratory and on field (on test cells). This project allowed for direct involvement in the design, installation, and validation of a monitoring system, understanding its potential and limitations. The case study, particularly the monitoring of two identical test cells in terms of shape, size, materials, exposure, and building systems, built to compare the prefabricated facade module with a non-prefabricated building case, is presented here as emblematic in its simplicity.

3.3 What to measure? How?

3.3.1 Physical and environmental factors

The literature [226], [227] has extensively examined the four primary conventional comfort aspects within the context of Indoor Environmental Quality (IEQ) in buildings: **air quality, hygrothermal conditions, visual environment, and acoustic environment**. Although all these **factors** are closely linked to the well-being of occupants, as well as energy and sustainability issues, as illustrated in Figures 2.1 and 2.2, they are just one aspect describing the starting "situation" of the human-building interaction. However, these factors **are the most readily quantifiable** and are thus frequently used to assess indoor space quality. Typically, these four environmental areas are assessed through microclimatic parameters and on-site monitoring in several research campaigns [228], , complemented by subjective feedback from building occupants (see Section 3.3.2).

This section not only provides insights into various Key Performance Indicators (KPIs) and assessment methodologies but also presents regulatory values and thresholds for each of them. Some environmental parameters appear in multiple standards, and it is not uncommon to encounter varying requirements for the same indicator. This lack of standardization introduces uncertainty, making it challenging to navigate regulations, interpret specifications, and understand the required performance levels. The objective of this part of the study is to simplify such interpretations and establish a common framework for identifying a set of KPIs and evaluating appropriate thresholds. The main findings, divided by IEQ domain, are reported below, from Tab. 3.1 to Tab. 3.4. Below each table, a brief list, derived from bibliographic research and field experience, of the most common sensor technologies for monitoring and their best positioning is presented. For an overview of occupant behavior and occupancy monitoring methodologies, here not covered, please refer to Ji et al. [229].

Hygro-thermal environment

Tab. 3.1 Current available standards and conventional parameters for the hygro-thermal environment

HYGRO-THERMAL ENVIRONMENT		
Reference	*Conventional parameters and thresholds*	
ASHRAE 55	PMV/PPD method applicable with: $1.0 \leq met \leq 2.0$ $clo \leq 1.5$ $Av \leq 0.2$ m s^{-1} Mechanically conditioned buildings	$-0.5 < PMV < +0.5$ $PPD < 10$ %
	Adaptive comfort applicable with: $1.0 \leq met \leq 1.3$ $0.5 \leq clo \leq 1.0$ $Av \leq 0.2$ m s^{-1} Humidity ratio ≤ 0.012 kg · H_2O/kg Occupant-controlled operable windows	See ranges in: ASHRAE 55, Figure 5.3.1
	Standard effective temperature	Calculation of Adjusted PMV (PMV_{adj})
	Local thermal discomfort applicable with: $1.0 \leq met \leq 1.3$ $0.5 \leq clo \leq 0.7$	Expected PPD [%]: - Draft: < 20 % - Vertical Air Temperature Difference: <5 % - Warm or Cool Floors: < 10 %

			- Radiant Asymmetry: < 5 %	
UNI EN 16798-1	PMV/PPD method applicable with: mechanical heating/cooling			
	Category	PMV	PPD[%]	
	I	-0.2 < PMV < +0.2	< 6	
	II	-0.5 < PMV < +0.5	< 10	
	III	-0.7 < PMV < +0.7	< 15	
	IV	PMV < -0.7; or +0.7 < PMV	> 15	
	Design criteria: Operative temperature [°C]			
	Category*	Minimum for heating	Minimum for cooling	
	I	21.0	25.5	
	II	20.0	26.0	
	III	19.0	27.0	
	IV	18.0	28.0	
	*Assuming 50% RH and <0.1 m s^{-1} air velocity			
	Design criteria: Relative humidity [%]			
	Category**	For dehumidification	For humidification	
	I	50	30	
	II	60	25	
	III	70	20	
	**In occupied spaces with systems installed			
EN ISO 7730	Design criteria: Max mean air velocity [m s^{-1}]			
	Category	Summer	Winter	
	A	0.12	0.10	
	B	0.19	0.16	
	C	0.24	0.21	
	Local discomfort: PD [%]			
	Category	Vertical air temp difference	Warm/cool floor	Radiant asymmetry
	A	<3	<10	<5
	B	<5	<10	<5
	C	<10	<15	<10
	A	0.12	0.10	
	B	0.19	0.16	
	C	0.24	0.21	

When discussing hygro-thermal environmental conditions, the most frequently measured environmental variables are temperature, relative humidity, and air velocity. The prevalent sensor technologies [230], [231] for monitoring temperature, whether ambient or surface, encompass thermistors (comprising both negative temperature coefficients (NTCs) and positive temperature coefficients (PTCs)), Resistance Temperature Detectors (RTDs) (such as PT100 or PT1000), thermocouples and semiconductor-based sensors (usually incorporated into integrated circuits (ICs)). According to UNI EN ISO 7726 guidelines, mean radiant temperature is instead measured through globotermometer, an instrument that comprises a spherical cavity with a standardized 15 cm diameter and a 0.2 mm thickness, coated with lampblack and connected to a thermocouple. Sensors for humidity monitoring are divided into three types: capacity humidity sensor, resistive humidity sensor, and thermal conductivity humidity sensor. Air velocity is measured using anemometers (vane or hotwire). A comprehensive understanding of ambient temperature, relative humidity, mean radiant temperature, and air velocity, combined with clothing and metabolism levels, enables the calculation of the Predicted Mean Vote (PMV) index and subsequently the Predicted Percentage of Dissatisfied (PPD).

Regarding the positioning of temperature sensors, consideration must be given to the variable being measured and the purpose of the measurement. For the air temperature of a room, the sensor should be placed in the center of the room and at an intermediate height (avoiding the thermal gradient between the bottom and the top, more pronounced in rooms with a high floor height). The sensor should not be placed in areas directly irradiated by the sun or near moving air (open windows or HVAC air intakes or emission vents). To evaluate thermal gradients between different zones of the room, it is preferable to use a surface temperature sensor. For a correct evaluation of the mean radiant temperature, the globe thermometer should be positioned in a central position in the room, considering the viewing factors of the various building components. If the interest is not the room or the average occupancy, but the specific occupant, temperature sensors - air, surface, or globe - should be positioned at the location occupied by the occupant being analyzed. What has been said for temperature sensors also applies to humidity sensors, placing the sensor in a central area of the room if the interest is the space, and near more specific building components if the monitoring objective is more detailed.

Air quality

Tab. 3.2 Current standards and conventional parameters for the indoor air quality

AIR QUALITY

Reference	*Conventional parameters and thresholds*	
ASHRAE 62.1	Carbon monoxide	9 ppm [8h]
	Formaldehyde	0.1 mg m^{-3} / 0.081 ppm [30min] 27 ppb [8h] 45 ppb / 7.3 ppb [1h/8h]
	Lead	1.5 μg m^{-3}
	Nitrogen dioxide	100 μg m^{-3} 470 μg m^{-3} [24h]
	Odours	80 % acceptability
	Ozone	100 μg m^{-3} / 50 ppb
	Radon	4 pCi/L
	Sulphur dioxide	80 μg m^{-3}
	VOCs	Determined for each individual compound [Refer to: Table C-3]
	Particles <2.5 μm	15 μg m^{-3}
	Particles <10 μm	50 μg m^{-3}
	Ventilation rate	5 L s^{-1}· $person^{-1}$
UNI EN 16798-1	Carbon monoxide	For non-adapted persons: 550 ppm above outdoor for Cat. I 800 ppm above outdoor for Cat. II 1350 ppm above outdoor for Cat. III 1350 ppm above outdoor for Cat. IV
	VOCs *	< 1000 μg m^{-3} / < 300 μg m^{-3}
	Formaldehyde *	< 100 μg m^{-3} / < 30 μg m^{-3}
	*depending on low/very low polluting buildings	
	Design ventilation air flow for single-person office of 10 m^2 in a low polluted building (non-adapt- ed person)	1.0 l s^{-1} m^{-2} for Cat. I 0.7 l s^{-1} m^{-2} for Cat. II 0.4 l s^{-1} m^{-2} for Cat. III 0.3 l s^{-1} m^{-2} for Cat. IV OR 10 l/(s per person) for Cat. I 7 l/(s per person) for Cat. II 4 l/(s per person) for Cat. III 2.5 l/(s per person) for Cat. IV
IWBI, The WELL Building Standard	Formaldehyde	< 27 ppb
	VOCs	< 500 μg m^{-3}
	Carbon monoxide	< 9 ppm
	$PM_{2.5}$	< 15 μg m^{-3}
	Ozone	< 50 μg m^{-3}
	Radon	< 51 ppb
	PM_{10}	< 0.148 Bq/L

The Living Building Challenge V 3.1	Formaldehyde	< 50 ppb
	$PM_{2.5}$	< 12 μg m^{-3}
	PM_{10}	< 150 μg m^{-3}
	VOCs	< 500 μg m^{-3}
	$C_{12}H_{14}$	< 3 μg m^{-3}
	Carbon monoxide	< 9 ppm
	Ozone	< 51 ppb
	Carbon dioxide	< 750 ppm
	Nitrogen dioxide	< 0.053 ppm [24h]

Regarding air quality, other important references, also for outdoor conditions, are the EPA standards (National Ambient Air Quality Standards), WHO guidelines (Air Quality Guidelines for Europe), NIOSH (Pocket Guide to Chemical Hazards), and OSHA (Code of Federal Regulations). From a technological perspective, sensors used for air quality monitoring can be mainly categorized as optical, chemical, and electrochemical sensors [232]. The most common types are NDIR (Non-Dispersive Infrared), PID (Photoionization Detector), metal-oxide-semiconductor (MOS) sensors, and Electrochemical (EC) sensors.

The positioning of the sensor must consider the type of pollutant to be monitored. Some gases, because of their different density compared to air, tend to concentrate more upwards or downwards in the room. Also, it's important to avoid placing the sensor in directly sun irradiated areas or near moving air (such as open windows or HVAC air intake or emission vents), as this could affect the accuracy of the measurement. Continuous recalibration is necessary for almost all air quality sensors, which should be carried out by relocating the sensor and exposing it to an uncontaminated environment every few days, depending on overall performance of the sensor.

Visual environment

Tab. 3.3 Current standards and conventional parameters for the visual environment

VISUAL ENVIRONMENT				
Reference	*Conventional parameters and thresholds*			
UNI EN 12464-1 (for work places)	Activity	E_m [lux]	UGR	R_a
	Filing	300	19	80
	Writing, reading	500	19	80
	Graphic	750	16	80

	CAD desks	500	19	80
	Conference rooms	500	19	80
	Reception	300	22	80
	Archives	200	25	80
UNI EN 16798-1 (for work places)	E_m [lux]	500		
CIBSE, Daylighting Window Design Guide	Daylight factor	> 2% daylit rooms > 5% very daylit rooms		
BRE, BREEAM	Daylight factor	>2% for at least 80% of floor area		
USGBC, LEED	Annual Sun Exposure	< 10%		
	sDA	> 55% > 75 %		
IWBI, The WELL Building Standard	Equivalent Melanopic Lux (EML)	> 200 melanopic lux		

Existing standards provide visual comfort threshold values exclusively for workplaces, with a few considerations for residential buildings. From a technological standpoint, the measurement of illuminance is carried out using photodiodes or solid-state photocells, with the luxmeter being the primary instrument in use. For glare assessment, complex measurements of luminance are used, replaced in some cases by methodologies that employ HDR (High Dynamic Range) fish-eye images.

The sensor positioning is closely related to the measurement objective. For an average evaluation of the room's illumination, it would be necessary to create a regular grid of measurement sensors at a specific height (0.8m is, for example, the most recommended by research and building certification protocols). This is usually very complex to implement in practice, given the discomfort it would create in the use of space: therefore, representative points are preferred. For the evaluation of visual comfort (illumination and glare) in specific positions, the sensor should be placed in the exact position to be monitored. For glare, it is necessary to assess the entire visual field of the observer and take measurements for as many solid angles as possible.

Acoustic environment

Tab. 3.4 Current standards and conventional parameters for the acoustic environment

ACOUSTIC ENVIRONMENT

Reference	*Conventional parameters and thresholds*			
UNI EN 16798-1	Equivalent continuous sound level $L_{eq,\,nT,A}$ [dB(A)]			
	Room	Cat I	Cat II	Cat III
	Living	≤30	≤35	≤40
	Sleeping	≤25	≤30	≤35
ASHRAE 189.1	Max sound pressure level L_{max} [dB(A)]			
	Room		Daytime	Nightime
	Living and Sleeping		<50	-
	Sleeping		-	<45
CIBSE Guide A, Environmental Design 2015	Max sound pressure level L_{max} [dB(A)]			
	Living areas		<35	
	Kitchen		<40/45	
	Sleeping areas		<30	
IWBI, The WELL Building Standard (for offices)	Average sound pressure level from outside noise intrusion (dining areas)		≤ 55 dBA	
	Reverberation time (RT60)			
	Dining areas		1 sec	

Additional significant regulatory references containing reference values for acoustic comfort can be found in the New Zealand standard AS/NZS 2107:2016, the British standard BS 8233:2014, and the WHO Guidelines for Community Noise 1999. Sound level meters consist of several components: the transducer, which, if the medium of propagation is air, is the microphone (capacitive, piezoelectric, condenser, or MEMS - Micro-Electro-Mechanical Systems); the amplifier, used to amplify sound levels, especially low ones; the weighting circuit or filter bank; the integration device, and the external equipment, which allows direct measurement reading on the display and potential data storage.

The positioning of the acoustic sensor must be carefully evaluated because it is easily able to record noise sources that are not intended to be included in the analysis. Tipically, monitoring campaigns are not carried out without an operator, whose presence is essential to note particular situations and noise sources not to be considered.

Energy

Within the physical environmental parameters to be measured, we can also include energy, both for gas and electricity consumption. Defining threshold values for these parameters is very complicated as they are dependent on many variables, so when speaking of energy, it is often referred to as efficiency, i.e., the quality of achieving the largest amount of useful work using as little effort as possible. This effort is intuitively different depending on the needs of the user, the size of the building, weather conditions, and much more. The references, in Europe, on the building side, therefore become the Energy Performance of Building Directives, while for individual devices the consumption values are found on energy labels.

To measure electrical and gas absorptions in situ, the easiest way is to consult utility bills, with the common limitation that it is difficult to digitalize the data and that it is not always possible, given the lack of records, to reconstruct a continuous time series. Today, however, technology for reading electricity consumption has developed, reducing cost and invasiveness, and resulting in several methods and devices available for this purpose. Smart plugs (based on a shunt resistor) are small devices that can be inserted between an electrical outlet and an appliance to monitor and control its power consumption. They often connect to a mobile app or central hub, allowing energy use to be monitored remotely. Current clamps (CTs) are sensors, or rather current transformers, that, when attached to electrical wires, measure, in some cases alternately exploiting the Hall effect, the current flow, and can provide real-time data. They are "passive" sensors that must wrap around the conductor to function, which, in a single-phase system, can be the phase or neutral electrical wire. Compared to smart plugs, they are slightly more invasive because they must wrap precisely one of the three wires of the classic electric cable, which must be specially stripped and prepared. Lastly, there are "pass-through" sensors, such as smart meters, which are designed to be placed between the power supply and the circuit load. Installing these sensors requires the expertise of an electrician as they directly modify the electrical system. Access to the raw electrical consumption data measured by the smart meter is generally straightforward.

When it comes to gas consumption, the challenges are similar, but the opportunities for employing low-cost and minimally invasive sensors are quite limited. In Italy, for instance, gas consumption in residential buildings is mainly managed through meters with remote reading capabilities. However, real-time information is not directly accessible to the user unless specifically requested. There is also the possibility of using "pass-through" sensors, but these require the expertise of highly trained personnel. More basic technologies include optical sensors capable of detecting the light pulses emitted by the meter, which can be correlated with instantaneous consumption. Alternatively, inside the gas meter, a typical mechanism incorporates a magnetic element, usually a small magnet, affixed to a moving part. As gas flows through the meter, this moving part rotates or oscillates. During each rotation or movement, the magnetic component passes by or through a magnetic sensor that measures consumption. The use of heat meters directly connected to the gas-fed hydraulic heating or cooling system is an additional alternative, once again with necessary installation precautions.

3.3.2 User-related elements

Adhering the categories outlined in Fig. 2.2, **in addition to physical and environmental factors, evaluating comfort within architectural spaces also requires measuring mental well-being and sense of “freedom”**. These parameters are inherently difficult to quantify in advance, often requiring exploration of areas of the humanities and social sciences, psychology and sociology [233], [234]. For the sake of brevity, this section focuses on common approaches to data collection related to non-quantitative aspects in the academic and regulatory literature. Although it has been demonstrated that measurable factors, such as access to natural elements, external views, and the provision of adequate natural light, affect individuals' mental well-being [235], **a more thorough investigation of how indoor environments affect people's psychological well-being**, as well as their general perception and satisfaction, generally **results in the adoption of Post-Occupancy Evaluation (POE) techniques**. POE, as defined in the scientific literature, refers to “… the process of evaluating buildings in a systematic and rigorous manner after they have been built and occupied for some time” [236]. It is commonly employed as a versatile term encompassing two dimensions: an examination of the project delivery process and an assessment of the technical and functional performance of the building throughout its occupancy.

Decisions pertaining to Post-Occupancy Evaluation (POE) and monitoring techniques are shaped by contextual variables, encompassing aspects like the building's location, its category (e.g., residential, school, commercial, etc.) and the nature of the problem to be addressed (e.g., temperature, humidity, air quality). The context, which includes the building's actual condition, the occupants' needs, and the available resources, significantly influences also the choice of monitoring tools, as elaborated in Section 3.3.1, and inform the selection of one of three distinct POE methodologies [237], [238]:

- Transversal: this procedure is employed for rapid occupant satisfaction assessments of indoor environmental qualities or building features. It relies heavily on questionnaires and surveys, which include scoring, discrete scales, and open-ended questions. While it is useful for benchmarking, it may not capture the nuanced complexities of building occupancy.
- Point in time: Point in time refers to the collection of "real-time" information on perceptions provided by occupants, gathered through sensors placed on mobile carts or specific on-site or portable instruments. These measurements are collected at specific times, not necessarily repeated, usually during specific experiences, events, or campaigns. The data is then analyzed later on.
- Longitudinal: such investigations are employed to assess the perception of environmental comfort and the ongoing changes in indoor environmental conditions over a specific duration. In this assessment approach, linking questionnaire responses, often with a limited number of simplified (e.g., binary) answers, to IEQ parameter measurements necessitates the deployment of sensors, whether fixed or wearable, and, sometimes, Occupant Voting Systems [239].

Although there is no one-size-fits-all approach to conducting building comfort and energy consumption surveys, some valuable guidance can be drawn from UNI EN ISO 10551 and UNI EN ISO 28802. Typically, a survey questionnaire can be customized to collect general information, demographic, and anthropometric data of occupants, capturing their perceptions and satisfaction levels regarding various aspects of indoor environmental quality (IEQ) and energy consumption. A comprehensive list of Post-Occupancy Evaluation (POE) protocols is available in [237], which details factors such as methodology, types of assessment, categories analyzed, compatibility with green building certifications and other standards, building types commonly assessed, and availability of online resources. In this context, the following abbreviated list is provided, underscoring the sustained concern in this field:

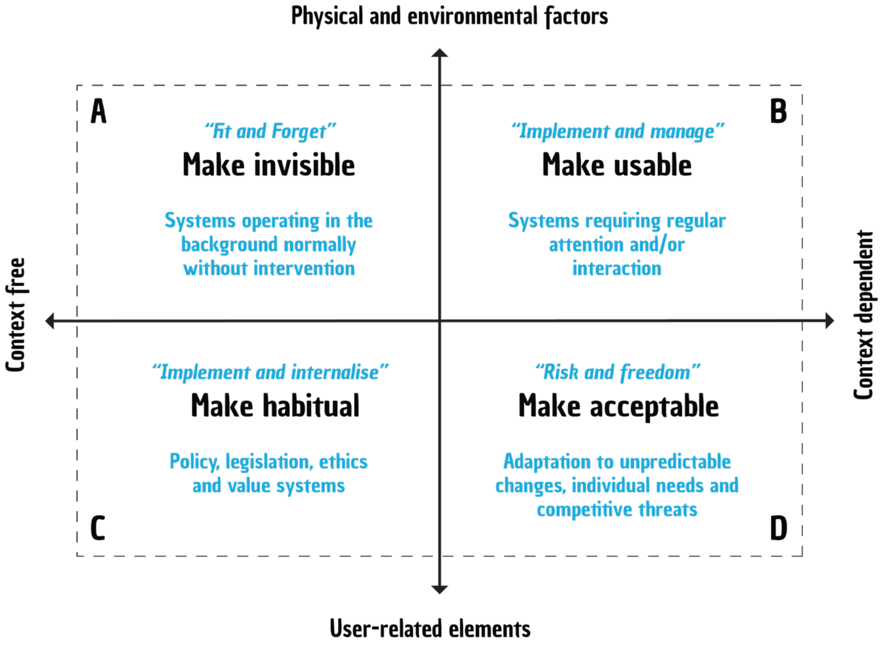
- CBE Occupant Survey
- BOSSA TIME-LAPSE
- SNAP-SHOT BOSSA
- BOSSA NOVA
- BUS
- Space Performance Evaluation (SPEQ)
- Leesman Index
- Occupant Comfort & Wellness Institute Built Environment
- Comfortmeter
- Be well Laed well
- OHFB Afriforte

While standards provide guidelines for gathering user feedback and conducting energy audits, a structured and consistent method for systematically implementing subjective assessments, particularly regarding personal perceptions, is notably lacking. Consequently, subjective evaluations frequently rely on researchers' expertise, leading to data that proves challenging to integrate into a comprehensive database. Considering that occupants play dual roles, being both active users capable of adapting their environment to their needs and passive residents subject to the indoor conditions that can impact their comfort and well-being, it becomes nearly inevitable to employ interviews and focus groups as a means of assessing qualitative aspects. This approach, however, tends to decrease the scalability and reproducibility of the measurement method, which often fits specifically to the person being interviewed and collect often "noisy" data.

If the intention is to assess a building's comfort and energy consumption, it is imperative to gain a clear understanding of the occupant's perspective**. Often, in contrast to the assumptions made by technical experts, residents** predominantly view buildings as tools for achieving their objectives. They typically **exhibit minimal interest in design or management matters and are primarily focused on the efficient execution of their tasks and activities with minimal disruption**. It is essential to consider subjective and sociocultural factors (as discussed in Section 2.3) during the evaluation process. These factors can significantly impact the definition of a comfortable building, which may be the result of a healthier lifestyle and increased opportunities for occupants to take breaks from their daily indoor routines by spending time outdoors rather than intrinsic physical differences in the buildings themselves.

Leaman [240] offers a systematic and interesting perspective on this topic, slightly adapted and incorporated in Fig. 3.1. The author identifies four design strategies: "make invisible", "make habitual", "make usable", and "make acceptable". Significantly, these strategies can also serve as **potential measurement parameters: "invisibility", "habitualness", "usability", and "acceptability"**.

Fig. 3.1 Design strategies that fits user need perspective.
"Context-free" pertains to universally applicable principles, rules, and processes, independent of specific situations, while "context-dependent" factors are determined by local conditions and circumstances. Adapted from [240]



In Leaman's own words, "invisible" pertains to elements designed to operate seamlessly in the background with minimal or no human intervention. "Usable" encompasses elements that require regular attention and interaction, a concept closely linked to management practices and occupant convenience.

"Make habitual" refers to both formal and informal rules that facilitate safe, comfortable, and smooth operation. "Acceptable" includes elements that go beyond prescribed regulations, allowing for individuality, innovation, and adaptability. More generally, building technologies and systems should be designed to operate seamlessly in the background, requiring minimal ongoing management oversight. When intervention becomes necessary, user interfaces should be straightforward and provide clear feedback regarding their operational status (i.e., whether they are functioning) and their impact (i.e., the changes they've induced). Users should have the ability to override these systems, ensuring they always have alternative options, particularly in emergency situations. The system should possess sufficient "degrees of freedom", "carrying capacity", or "redundancy" to handle unforeseen changes, such as unexpected increases in occupant density. Consequently, the building and its components/resources (as will be discussed in Section 4.3.3) are seen as versatile and adaptable. **The greater the number of resources and their adaptability, the higher the comfort level, the greater their efficiency the greater the energy savings. The quantity of these resources can therefore also become another measurable key performance indicator**.

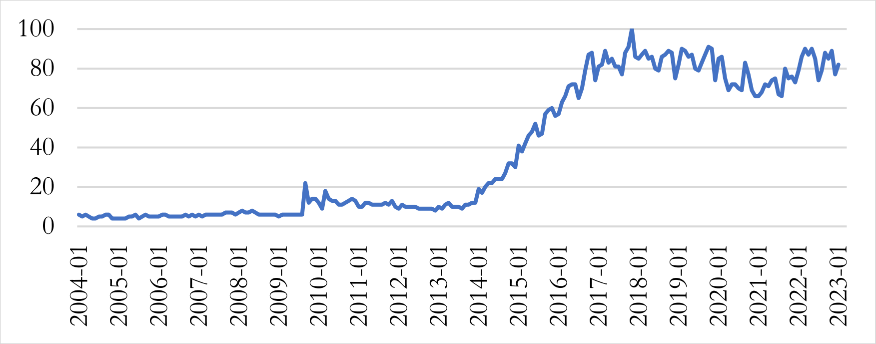
In this context, the world of **IoT and smart home**, as introduced in Section 1.1 and as further discussed in the next paragraph, undoubtedly provides a promising solution, **serving both as a measurement system and as a flexibility system that can facilitate the connection between users and building components**. A tool, however, that should not embrace the contemporary tendency to place everything in quadrant A of Fig. 3.1 (fit and forget), typical of a globalized market- and supply-chain-driven view of the built environment, which ultimately risks forgetting the real needs of users.

3.4 Emerging technology: IoT and smart home

The origin of the term IoT can be largely attributed to Kevin Ashton in 1997 during his work at Proctor and Gamble, where he employed RFID (Radio-Frequency IDentification) tags to streamline supply chain management [241]. Since then, IoT has evolved significantly beyond its initial use with RFID tags, growing into a complex ecosystem and industry. In 2011 the number of connected devices on the planet overtake the number of people [242]. By 2023, IoT market is anticipated to achieve a revenue of approximately $1,177.00 billion with an annual growth rate of 13.60%, leading to a market size of about $2,227.00 billion by the year 2028 [243]. The original concept of connecting "things" to the Internet, enabling them to be accessed "anytime, anywhere, by anyone and anything", was primarily associated with devices like smartphones, tablets, PCs, and laptops up until 2012 [244]. However, over the past decade, the **IoT concept has expanded to encompass a wide array of applications**, including healthcare, utilities, transportation, and various services, as discussed by Gubbi et al. [242].

Undoubtedly, the term IoT has gathered considerable attention and enthusiasm. This is evident in the widespread popularity of the buzzword and statistical trends: the issuance of patents has experienced substantial growth since 2014, along with a notable increase in Google searches and the publication of IEEE peer-reviewed articles [244] (Fig. 3.2).

Fig. 3.2 Global interest in the IoT topic over time (Google Search)
Numbers represent search interest relative to the highest point on the chart for the given region and time. A value of 100 is the peak popularity for the term. A value of 50 means that the term is half as popular. A score of 0 means there was not enough data for this term.



In contrast to the anticipated IoT revolution, however, recent research suggests that the adoption of IoT may be proceeding at a slower pace than initially estimated, as noted by Sorri et al. [245]. Several factors contribute to this deceleration, including challenges in implementation and issues related to the standardization of IoT platforms, connectivity, business models, and defining killer applications. Nevertheless, the need for IoT technologies remains evident, closely intertwined with ongoing technological advancements and the process of digitalization, which require effective connectivity among various electronic devices. IoT is being utilized across various sectors, from industrial sector to smart cities, but also transportation, intelligent energy management in buildings, power grid oversight, and agriculture [246].

In all these domains, in fact, there is a growing need for more efficient services and adaptable processes, which can be achieved through the effective implementation of IoT technologies and data collection. This holds true in the realm of smart buildings as well. If by "intelligence" we refer to the capability of integrating and optimizing the building system (see Section 1.2), it becomes evident that, potentially, the more data available, the better we can understand how a building performs and what the user expects from it. This, in turn, simplifies the optimization of human-building interaction, as pointed out by Stojkoska [247].

The concept of technologies aimed at improving the quality of life in homes or, more broadly, in human-made environments is certainly not new and can be traced back to the field of "domotics" (derived from "domus," Latin for home, + "robotics")[248]. Depending on the type of building to which domotics is applied, two distinct macro-categories can be identified: Home Automation and Building Automation. In the first case, we refer to an automation process that involves a single apartment or a small-sized residence, aimed at automating the management of all household appliances to enhance system performance. In other words, in addition to the basic services provided related to electrical and technical systems, the domotic system must also be capable of offering additional services, such as entertainment and leisure functions, to improve domestic comfort. For these reasons, the system must be able to "communicate" with users and meet all their needs in real-time. In the second case, Building Automation can manage broader and more complex applications that encompass the entire building, such as hotels, theaters, universities, and museums. In this scenario, the system must define in advance the various types of services it must provide at the time of installation, encompassing both simple and complex functions such as energy-saving management, access control, and building security. The distinction between Home Automation and Building Automation, where the former was traditionally seen as a subset of the latter, is becoming less pronounced due to the rise of IoT and the growing number of devices capable of communication and transmitting various types of information. The range of functions managed by a BACS (Building Automation and Control System), including

HVAC maintenance services, fire detection and alarm, security access and control, intrusion detection, environmental control, energy information management, energy supply and load management, smoke control, and lighting control, can now also be achieved by a compact Home Automation System (HAS), which is more flexible and less invasive.

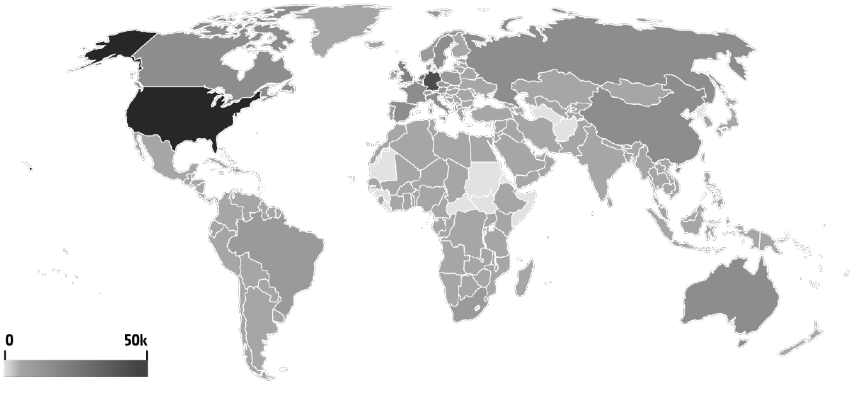
The market is currently flooded with **Home Automation platform**, which have the benefit of establishing a **direct connection with customers**, particularly when voice control is used to improve communication between the user and the home automation system (VCHAS: Voice Controlled Home Automation System). Their proliferation is undeniable, as even major high-tech commercial companies, initially renowned for other flagship products, such as Apple, Google, Amazon, Samsung, and Philips, have ventured into this field, reaching users who may not be tech-savvy. Beyond the widely marketed Alexa, Google Home, and Apple HomeKit, the market offers a plethora of diverse products and solutions that, on one hand, have opened up the world of optimizing living spaces, often focusing on comfort and energy efficiency [249]. On the other hand, due to limited customization opportunities for obvious product business model reasons, they struggle to position themselves as a complete replacement for a BACS or, more generally, a traditional environmental and energy monitoring system. The collected data, rather than benefiting the user in understanding and enhancing the performance of their home, remains at the disposal of the respective company, primarily utilized to improve their own product rather than the space in which it is installed.

However, the development of IoT has led to a simplification and increasing user-friendliness of DIY (Do-It-Yourself) home automation systems that were once the domain of makers, technology enthusiasts, and early adopters. Unlike proprietary platforms with closed-source code controlled by their respective companies (e.g., Zibase, eeDomus, Crestron, Vera 3, HomeSeer, Zipabox, Control4, Fibaro, etc.), open-source solutions may have a slightly more complicated interface, but the level of integration and customization is exceptionally high. Also in this context, there are now numerous solutions available, such as Home Assistant, openHAB, Domoticz, Jeedom, FHEM, ioBroker, Node-RED, Calaos, Mozilla WebThings Gateway, LinuxMCE, Freedomotic, MajorDoMo, Pimatic, Domogik, DomotiGa, MisterHouse, etc.

Home Assistant [250] is perhaps the most robust and widely recognized open-source home automation platform, known for its extensive adaptability and control capabilities within the context of smart home management. Home Assistant boasts comprehensive compatibility with diverse devices, protocols, and services, simplifying the seamless integration of a variety of smart devices into the home environment. Benefitting from a vibrant community of dedicated developers and users, it offers a wealth of custom integration options and invaluable resources. A noteworthy aspect is its steadfast commitment to local control, thereby enhancing security and preserving privacy. The platform further distinguishes itself through its customizable web interface, known as Lovelace, empowering users to craft tailored dashboards, as well as the capacity to craft intricate custom automations through YAML scripting. Home Assistant maintains an agile development cycle with frequent updates and the incorporation of new features. Moreover, it stands out by its capacity to be voice-controlled, akin to more commercially-oriented platforms such as SmartThings, Apple HomeKit, and Google Home. In fact, it possesses the unique ability to encompass these systems as subordinate subsystems within its ecosystem.

An objective literature-based comparison between VCHAS is currently unavailable due to the novelty and continuous development, as well as occasional failures, of these platforms. However, insights can be gathered from the Home Assistant website analytics (https://analytics.home-assistant.io/).

Fig. 3.3 Home Assistant installation worldwide in September 2023.
Source: https://analytics.home-assistant.io/



In September 2023, there are approximately 252,609 Active Home Assistant Installations worldwide, a number that is likely rounded down, since the data reporting for actual home automation system installations is entirely voluntary, and users can choose to revoke this permission at any time. Furthermore, these statistics account for active installations, meaning individuals who may have abandoned the platform for another are not included in this count. A closer look at Fig. 3.3 highlights the worldwide adoption of the platform, ranging from 45,810 installations in the United States to 9,278 installations across Africa.

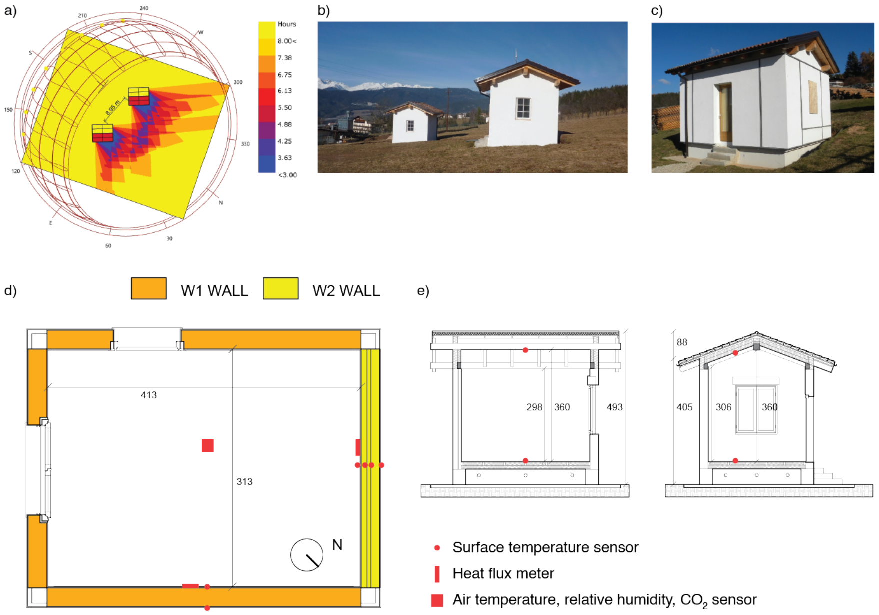
Given that Home Assistant, along with other HAS, can now collect data on indoor environmental quality (IEQ), comfort, user behavior, and energy consumption at a level comparable to or even exceeding that of traditional academic research tools for environmental and energy monitoring, and considering that the number of installations surpasses three times the sample size of 109,033 entries in the ASHRAE Global Thermal Comfort Database II [251] (the largest reference database for big data-driven analyses related to comfort and energy), it is evident that **HAS platforms represent an innovative and powerful tool for advancing our understanding of human-building interaction**, user comfort and energy consumption. This extends not only to researchers but also to end-users, **in a genuinely user-centered approach** where data not only offer essential insights to different stakeholders but also can be promptly converted into automation or recommendations, providing a rapid and accessible means for residents to customize their home environment and align it with their preferences and desires.

3.5 Renew-wall case study: design, management and data analysis of energy and environmental monitoring of a building

The increasing availability of information from residential buildings, both online and offline, thanks to emerging technologies such as IoT, cloud computing, smart buildings, and augmented reality [252], offers significant possibilities. However, the abundance of data **doesn't always translate into an absolute advantage for understanding our environment**: data collection allows for answers to complex questions but exposes the risk of accumulating useless data, creating virtual "data graveyards" that go unused. The exact quantity of data to collect and the frequency of acquisition are not easily defined. More sources, types, and objects, combined with widespread distribution, can enhance the accuracy of information, but the costs and complexities in managing highly diverse data can present significant challenges. While specific and limited data favor achieving the desired meaning from a statistical perspective, excluding outliers or limiting the initial database doesn't necessarily expedite the process or guarantee the expected result, as sometimes these "secondary" data provide the appropriate answers [253]. The choice depends on the research objective and the initial question.

The Renew-wall project (See Section 3.1 for a brief description) not only becomes a valuable case study for understanding the design and maintenance of a **monitoring system** but also provides an opportunity to delve into these **issues** related to **data quality, its significance, and its visualization**.

Fig. 3.4 a) Shadow analysis: number of hours of direct sunlight received by the test-cells during the winter solstice; b) The two test-cells before retrofit; c) The retrofitted test-cell; d-e) Geometrical description of the experimental units and sensors placement (dimensions in centimeters)



Two identical prototype buildings represent the case study (Fig. 3.4), and, despite their relative simplicity and limitations, they highlight the numerous considerations required for effective energy monitoring. This underscores how every step, even the most basic, can significantly impact the quality of the information available to those assessing the effectiveness of the design solution or to the end-user, who can be strongly influenced by the numerical data displayed on the monitoring screen.

The typological and construction characteristics of the two test cells are detailed in [254]. Their energy-environmental monitoring system includes sensors for monitoring the performance of the building envelope (thermal flux meters and temperature sensors, both surface and layer by layer, for the Northeast (W1) and Northwest (W2) walls; surface temperature sensors for the ground floor and the roof), the indoor space (T-UR-CO2 sensor), and external weather conditions (T-UR, wind speed and direction, irradiance).

In the first year of monitoring, various analyses were conducted on the data collected by the system to ensure the proper functioning of the sensors, verify similarities in the thermo-physical behavior of the two cells, and highlight any discrepancies. In the second year, prefabricated Renew-wall façade modules were installed on one of the two test cells. The following paragraphs focus on the first year, which is valuable due to the perfect comparison between the two prototype buildings and serves to justify the accuracy of the data. Only by confirming identical trends in both prototype buildings was it possible to accurately assess the thermo-hygrometric improvement brought about by the designed retrofit system [255].

The previously described variables are continuously monitored using the integrated ECLYPSE Connected System Controller by Distech Controls, equipped with an Internet connection through an ADSL router for remote access via a web browser. The system does not include control over the thermal regulation system. The data monitoring and visualization platform was developed by Enerconsult Srl in Brescia in collaboration with the University of Trento. It allows cloud access to the continuously recorded data from the two prototype buildings, facilitating the quick download of required information onto local devices. Specifically, data is exported in .csv format from the online monitoring platform and processed using Python-based code through the Jupyter Notebook application. While it is possible to observe the monitored parameters directly on the ECLYPSE website, more advanced statistical analyses necessitate direct work on raw data. This involves weekly processing through a dedicated script, generating reports with templates created through code and markdown. This script, utilizing Python libraries including Pandas, Matplotlib, Numpy, Datetime, and Os, sequentially extracts data from the downloaded .csv files, corrects timestamps, checks for any outliers, assesses discrepancies or missing information, and generates graphs and tables for more intuitive visualization over various time intervals. Although coding demands an initial investment of time and effort, it significantly expedites the essential steps required for continuous monitoring with frequent report generation. In the following paragraphs, the main adjustments made in this regard are highlighted for the specific case study, divided according to the specific issues encountered.

Ensuring accurate sensor nomenclature and wiring

Considerable attention is essential during the initial phases of installing the monitoring system: accurately labeling the sensors and ensuring precise wiring to the electrical panel is a critical process. Accidentally reversing the connections between the sensors, even due to a minor oversight, can result in significant challenges during analysis, expensive on-site verifications, and unjustified uncertainties about the behavior of the monitored parameters.

Missing data

Occasionally, power outages, disruptions in Wi-Fi data transmission, electrical connection malfunctions, or, more rarely, the consequences of exceptionally severe weather events can lead to gaps in the recordings that can negatively impact the data analysis. Python libraries, particularly Pandas, offer excellent flexibility when it comes to handling missing data. It is indeed possible to:

- Replace the null value by assigning a known prior data: this method is particularly valid when the same parameter is monitored by more than one sensor; the missing value from one of the sensors can refer to that measured by the "copy" sensor.
- Propagate the preceding or succeeding value of the missing data to fill the gap: this choice is advisable for parameters that are particularly stable over time, and its validity depends, clearly, on the size of the gap to be filled.

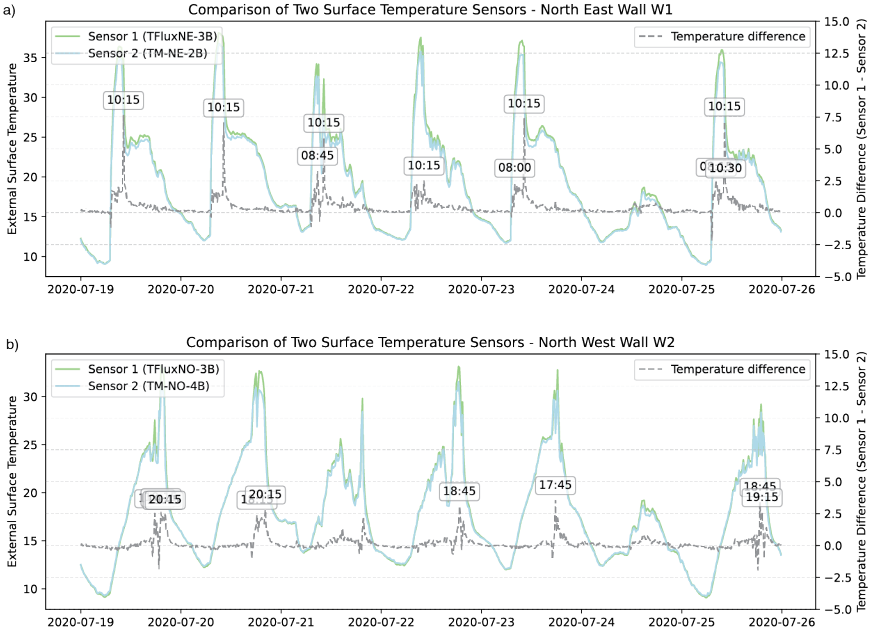
- Reconstruct the missing data through linear interpolation: this is the simplest choice, although it is not recommended for trends characterized by significant fluctuations.
- Reconstruct the missing data through interpolation using curves of a degree higher than the first: this is the preferable method for most data from environmental monitoring. It should be avoided for discrete variables (e.g., heating system operating status).

The lack of communication between the monitoring sensors and the acquisition system often results in different data depending on the type of sensor used. In this specific case study, the indoor temperature sensor communicates a "0", which differs from the "ND" or "100" values for indoor humidity and surface temperature sensors, respectively. It is crucial, therefore, to know, in advance, for each type of sensor, the output value corresponding to "data missing" in order to subsequently clean the entire data series. While it is straightforward to remove the "ND" or "100" values, when dealing with temperature readings of "0", removing this data by extension could coincide with the deletion of real information, as it may not be correct to exclude a priori an indoor temperature of 0°C. In such cases merely calculating mean values, which may represent the data displayed on the monitoring platform or the final output of the analysis, could lead to misunderstanding the actual behavior of the buildings. The simplest solution is to observe the variance and the root mean square error, which, when high, indicate a potential error in considering only the mean, minimum, or maximum values as reliable. The choice of the methodology for filling missing data filling primarily depends on two factors: the type of variable (discrete or continuous) and the number of consecutive NaNs (Not a Number) to fill.

Sensor positioning and placement

To verify the perfect match in the energy behavior of the two cells, particular attention must be given to the installation of the sensors, whose placement must be replicated identically on both prototypes. As evidence, Fig. 3.5 shows the trend of outdoor surface temperature measured on some summer days on the W2 northwest (Fig. 3.5a) and W1 northeast (Fig. 3.5b) walls of the same test cell, through two sensors per wall positioned just 10 cm apart.

Fig. 3.5 a) Trend of external surface temperature for the North-East wall W1 (a) and North-West wall W2 (b) and the difference between the two sensors.

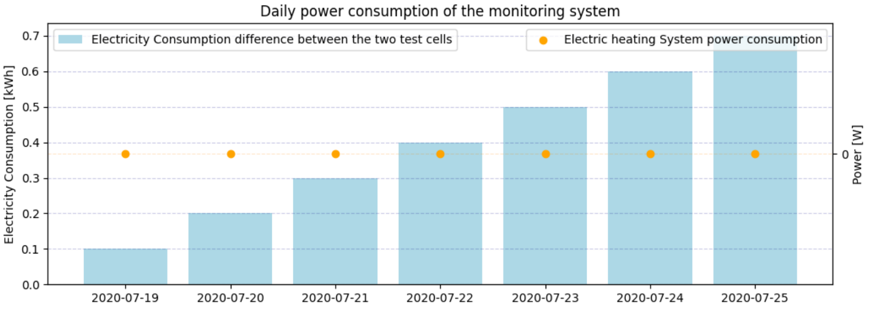


The deviation in the temperature peak at sunrise or sunset (10:00 am for the east wall, owing to shadows cast by the mountains, 6:30 pm for the west wall) is evident and linked to a different angle of incidence on the sensors of the sunlight, affected by the shading due to the overhang of the roof.

Power consumption of the monitoring system

The positioning of the power in the electrical circuit meter for measuring energy use should not be underestimated, considering the equipment for monitoring, installed power outlets, and the consumption of the external weather station. In this case, with the heating electrical system turned off, it measures an energy surplus (Fig. 3.6) for one of the two cells. If this difference is noticeable and consistent, it can be easily adjusted in data wrangling.

Fig. 3.6 a) Difference in total energy consumption between the two test cells with heating systems and lights off (the only remaining electrical load is the monitoring system).



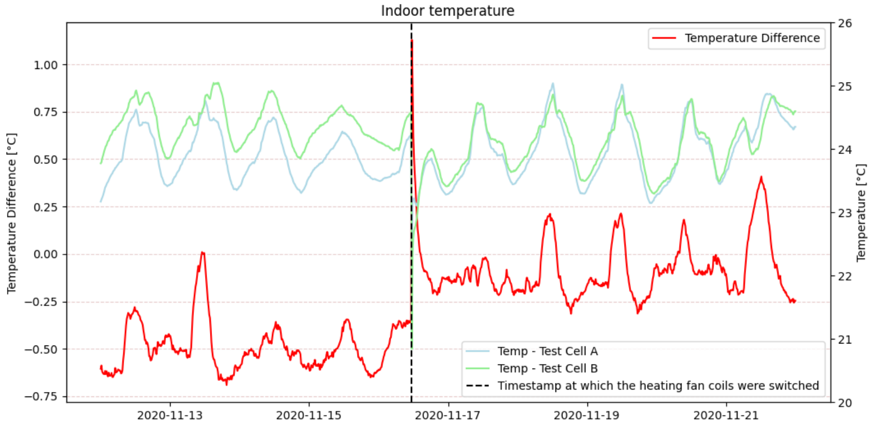
It's interesting to note that the monitoring system itself has its electrical consumption, which should be considered when describing and utilizing it as a tool for optimizing electrical consumption. The energy savings achieved through supervision must be reduced by the electrical energy used by the system (in this case, slightly less than 1 kWh per week).

Influence of additional variables

To exclude the influence of the type of heating system on the monitored environmental parameters and to verify some small differences in the measured electric consumption, a short monitoring campaign was conducted by swapping and repositioning the two electric floor-standing fan coil unit that heat the rooms. This campaign, limited to surface floor temperature and ambient temperature parameters, revealed the impact of the heat generator:

- limited but noticeable on the roof surface temperature
- limited but noticeable on the floor surface temperature
- evident on ambient temperatures (Fig. 3.7).

Fig. 3.7 Indoor ambient temperature trend and difference between the two cells pre and post inverting fan coils.

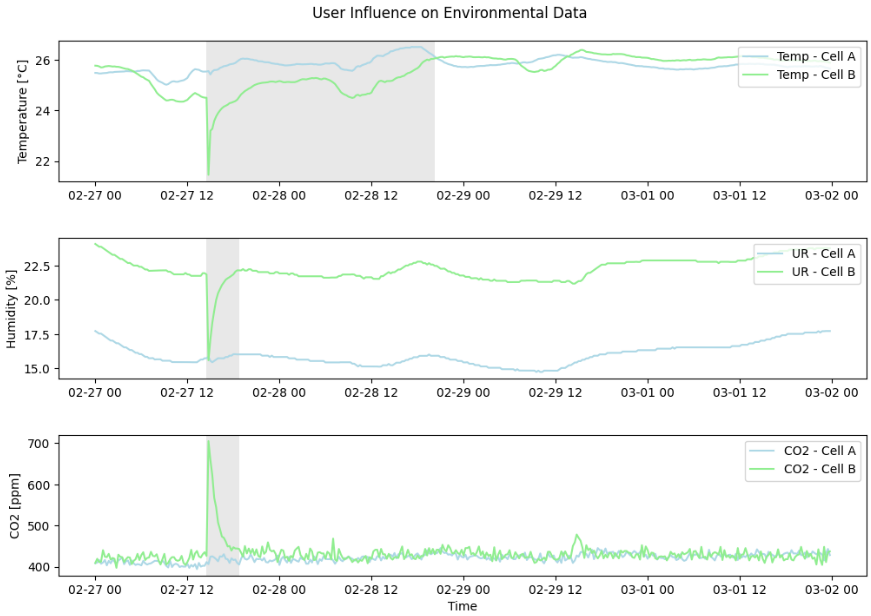


The underlying reason can be attributed to potential variations, even if minor, in the internal settings of the fan coil unit, particularly concerning the integrated thermostat and the fan. Despite these settings being deliberately identical and thoughtfully planned, it cannot be excluded that differing air movements within the cells, primarily due to external infiltrations, could impact the recorded data. This highlights that even in the most straightforward and controllable case study, there may be factors that affect the trends in environmental variables, sometimes more so than the inherent precision and accuracy of the sensors. It is the expertise of the technicians involved that enables the identification and removal of these secondary variables.

User influence

Among these "secondary" variables, we must also consider the occupants, here represented by the personnel who enter the prototype buildings at irregular intervals for maintenance and inspections. To ensure precise monitoring, every entrance, whether by authorized or unauthorized individuals, into the test cells must be diligently coordinated and closely observed. Fig. 3.8 emphasizes the impact of opening the access door and the presence, even if temporary, of an individual on the levels of CO2, indoor relative humidity, and temperature in cell B.

Fig. 3.8 Impact of user entry into Cell A and the discrepancies compared to Cell B.



Once more, within an automated process that entails the automatic computation of average values for the measured environmental parameters, neglecting to exclude these values can lead to substantial errors. Specifically, regarding indoor temperature, the impact of personnel entry does not dissipate within a few hours, as is the case with CO2 and relative humidity. Instead, its effect can persist, especially considering the opening of doors and windows and the infiltration of external air, for several days, which is the time required to restore thermal equilibrium between the two cells.

3.6 Main outcomes and concluding remarks

Despite the considerable variability and subjectivity of perceived comfort and residential energy consumption, there are well-defined standards and regulations that can serve as an initial reference point for measuring these parameters. However, to delve deeper into occupants' perceptions and satisfaction levels, a more in-depth investigation is required, involving interviews and focus groups even more than questionnaires. As emphasized by Molina [49], **measuring comfort and energy consumption** becomes **a demand from users** when there is an event or change that, in Molina's interpretation, raises awareness and draws attention to a problem. In the more technical and technological perspective of Leaman [240], it occurs when the building system no longer operates in the background, necessitating continuous intervention and, more broadly, is unable to flexibly adapt to unforeseen changes, typical of a residential environment. Just as the building components, **a monitoring system must be invisible, usable, accepted, and integrated into people's habits, respecting their privacy and preferences**. It must also be a useful, reliable tool capable of providing representative, real, and faithful data of the analyzed situation.

The collection and management of data involve a significant expenditure of time and energy: the design and implementation of a monitoring system and its related sensors, in fact, presuppose a significant initial investment, not always balanced by the usefulness of the processed data. It is not uncommon to observe a redundancy of incoming information, which sometimes risks resulting more in a difficulty in data processing than in a real benefit obtained through the comparison of similar information. The redundancy and the poor communicative capacity of the collected data are two factors contributing to the limited engagement often associated with the development of energy-environmental reports, which, regrettably, frequently end up in the hands of a restricted audience, failing to provide genuine value to the end users living in the monitored space. Monitoring should be structured in coherence with the questions that drive the need for comfort and energy analyses. Simultaneously, it must be adaptable to the specific context, leveraging constantly evolving technologies such as the Internet of Things, which not only generates data but can also guide users through recommendations and automations. It is in this context that the world of the **smart home** presents a unique opportunity, **bridging the gap between research and the daily routines of building occupants**, aiming to give data collection, as well as comfort and energy definitions, a more subjective and user-centered essence.

4 OPTIMIZE BUILDING PERFORMANCE WITH DATA

> *"We can't solve problems by using the same kind of thinking we used when we created them."*
>
> ALBERT EINSTEIN

4.1 Background

In the realm of building performance optimization, data assumes a pivotal role, with buildings generating extensive volumes of information through various sensors, IoT devices, and monitoring systems. This data serves as a foundation for analyzing and enhancing building performance through diverse means [256]. For instance, it enables the monitoring of energy consumption patterns, thereby identifying opportunities for waste reduction and increased efficiency, leading to real-time adjustments in heating, cooling, and lighting systems based on occupancy and weather conditions. Furthermore, building data facilitates predictive maintenance, empowering facility managers to proactively schedule tasks and avert costly breakdowns. By leveraging data on temperature, humidity, and air quality, a comfortable and productive environment for occupants can be curated, directly impacting their well-being and productivity. Through the analysis of data on space utilization patterns, buildings can be optimized in layout, identifying underutilized areas, and potentially reducing the overall footprint. Lastly, data-driven insights actively support sustainable practices, spotlighting opportunities for integrating renewable energy, curbing waste, and implementing eco-friendly building materials. To fully harness the potential of data for building performance optimization, sophisticated data analytics and artificial intelligence techniques are frequently deployed [257].

Optimization in buildings often revolves around simulation models, where numerical simulations represent the system, and mathematical optimization models define the best energy-efficient envelope combinations [258]. These simulation results are then transformed into data format, serving as input for artificial intelligence (AI) and Machine Learning (ML) algorithms, which have gained popularity in this field [259]. ML, a data-driven approach, possesses the ability to self-learn and tackle problems based on existing data, making it a sub-category of the statistical model. By employing various algorithms and statistical models, ML analyzes data and predicts outcomes based on historical data. ML methods in the Architecture, Engineering, and Construction (AEC) industry are continually evolving [260], finding practical applications in energy prediction and management for envelope selection and optimization [261], in optimizing Heating, Ventilation, and Air Conditioning (HVAC) systems [262], monitoring and managing thermal comfort levels [50], and predicting occupancy patterns and behavior [263]. Ongoing research is still determining the most effective ML algorithm [55], but it is undeniable that ML is now part of our daily lives, both for those living in technologically advanced buildings and for consumers who, through voice commands given to a personal assistant on a smart home device such as those from Amazon, Google or Apple, have had their first interaction with AI in the built environment. As Barber and Krarti [264] emphasized, amidst the continuous advances in the speed and accuracy of computers and technologies, there is, however, a potential risk of neglecting the primary goal: understanding and enhancing the relationship between user and buildings. **When creating smart or technologically advanced housing solutions, the needs, preferences, and well-being of the occupants must be put first**. The focus should not only be on integrating advanced technologies and automation into the building, but also on ensuring that these technologies improve the lives of the people who live there [265]. While quantitatively determining the precise influence of user behavior on building performance may be challenging [266], numerous studies strongly suggest that it is a significant factor contributing to the gap between expected and actual performance [20], [267].

The following paragraphs critically analyze projects and solutions that incorporate the end user's perspective into data collection, extending beyond technological aspects. rom this discussion emerges the possibility of using the smart home with this objective, turning it into both a data collection tool and an informative and operational tool for occupants, capable of enabling occupants to understand and utilize the building's resources. This relationship between the building and its resources is explored in light of salutogenic theory (Section 4.3.2), which forms the basis of the new concept, defined at the end of the chapter, of the "*resourcient building*" (Section 4.3.3).

4.2 Methods and aim

Chapter 2 provided insights into the concepts of indoor comfort and energy in buildings, while Chapter 3 explored how to measure them and collect related information. This chapter explores how, through this information, a building's performance can be optimized and how the building must be reconsidered to ensure that monitoring data have real utility. Utility that must necessarily include the end user, because without his or her full cooperation even simple data collection risks being compromised.

The methodological approach involves a critical literature review of European case studies and funded projects that address both technological and human aspects of smart building concepts. The objective was to gain insights from those who have directly encountered these challenges and learn from their experiences. The choice to restrict the study to Europe is motivated by the central importance of the cultural component in this analysis: as extensively documented in Section 2.3, users' perceptions of comfort and energy and behavior are extremely linked to their socio-cultural context. Although Europeans cannot be considered as a homogeneous group, the selection of projects leaned towards European ones because they often draw from analyses conducted on local models, later consolidated under a common framework. Additionally, focusing solely on Italian neighborhood projects would have limited the scope, hindering a broader understanding of the issue.

The research was conducted in CORDIS [268], an online search engine and platform that provides access to research results and information related to European Union-funded research and innovation projects across various disciplines. The search query "“smart building” AND “comfort” AND “energy”" yielded 172 EU-funded projects (H2020 and HorizonEurope). Projects exclusively focused on urban context, smart grids, mobility, water scarcity, waste management, and nature-based solutions were excluded, as well as those only tangentially related to buildings. Projects developing specific HVAC components (such as AC units and smart thermostats), building envelope or smart materials were also excluded, along with those focused on policy discussions or certification systems. After these exclusions, 67 projects remained. Additionally, 13 more projects were included from the insightful deliverable of SmartBuilt4EU [269], a project aimed at promoting collaboration among stakeholders in the smart building value chain, showcasing their innovations, and identifying research gaps and policy recommendations to further support the adoption of smart buildings.

The review's outcomes serve as the basis for subsequent paragraphs, where a more extensive conversation unfolds, concerning the correlation between individuals and buildings and the need to place the preferences and well-being of occupants at the center of this interaction. In the last part of the chapter and within this context, salutogenic theory is briefly introduced and applied to the discussion. A new building concept, resulting from the entire doctoral research, is outlined and analyzed, forming the theoretical foundation for the core activities discussed in Chapters 5 and 6.

4.3 Results and discussion

4.3.1 User-centered data collection for building performance optimization: empowering users for behavioral change

The user plays a central role in the successful collection of building performance data. Without active engagement and participation, even simple data collection can be difficult [270]. Users might neglect to provide necessary input or disrupt the data collection process altogether, leading to incomplete or biased datasets. Additionally, if users do not feel confident in using BMS or see the relevance or value of sharing data, they may be reluctant to participate, hindering the overall success of the data collection initiative. **User engagement and satisfaction drive the real successful adoption and utilization of energy-efficient solutions or innovation technologies**, ensuring their long-term effectiveness and impact [271].

Energy behavior depends on several factors mainly related to the context: cultural and social models, climatic and environmental conditions, education, and economic status [272]. Hence, behavioral studies involve twofold aspects:

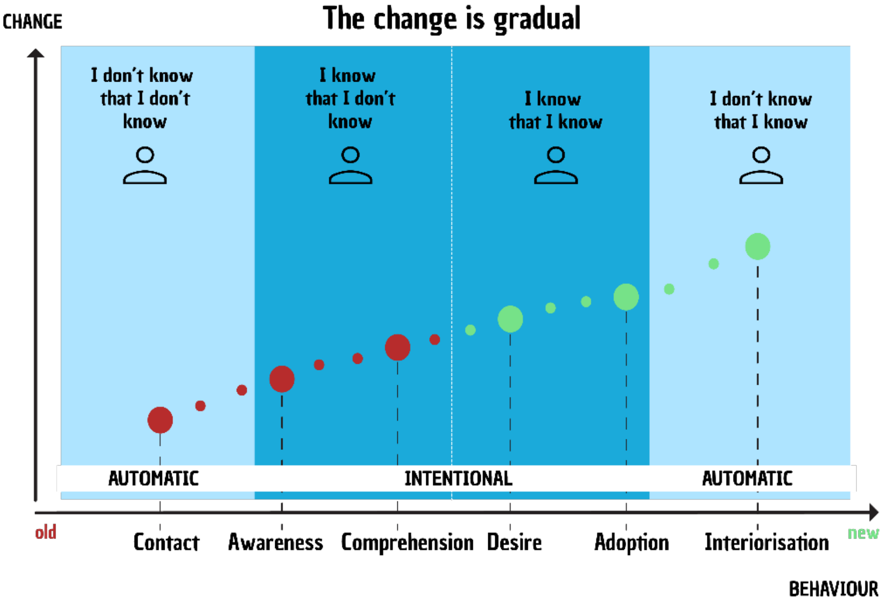
- Psychological: the changes depend on psychological mechanisms, such as emotions, values, beliefs, and motivations and/or the social innovation of governance and policy systems (for example the effectiveness of certain interventions or policies).

- Social science and governance: experimentation of social innovations addressing social, organizational, institutional, political and policy aspects

To drive a change in energy behavior, two issues should be considered: changes in attitude (e.g. acceptance of the new technology) and changes in the behavior itself (e.g. lowering energy consumption). The latter is based on two macro-components: a technical one, related to the energy systems, infrastructures, and technologies and a sociological one, related to the comfort perception, habits, and energy awareness [273].

To be effective, strategies and targets need to be in line with the motivations of individual building occupants and owners, and easily integrated with actions into daily behaviors [274]. **Changing the daily behavior is a major challenge**, since it requires training and awareness activities (Fig. 4.1), as well as feedback measures and incentives to trigger long-term change.

Fig. 4.1 The gradual three-step behavioral change process: automatic-intentional-automatic, leading from a state of unconscious incompetence to conscious competence. Adapted from [273]



Initially, occupants tend to take automatic actions, often with significant impacts, as they may be unaware or disinterested in potential improvements.

An initial contact is essential to raise awareness, transforming them into conscious users. As they realize the consequences of certain situations, their intention to improve is triggered, leading to the adoption of ongoing actions and strategies. In the last stage, corrective or improvement actions become internalized, and users implement them automatically.

This transition from automatic to intentional behavior, as mentioned, is influenced by several factors, extensively explored in behavioral theories [275], [276]. These factors are closely interlinked with the user's individual personality, motivation, behavioral beliefs, and contextual elements, such as discomfort, economic constraints, or social norms. Generally, individuals tend to prioritize short-term risks, such as economic slowdowns, over long-term risks, such CO_2 emissions or climate change [277]. Regarding practical implementations, Šćepanović et al. [278] present a well-defined classification of energy measures, encompassing:

- Structural Interventions: By modifying the building environment, occupants are encouraged to adopt energy-efficient habits. Examples include installing energy-efficient lighting, insulation, and automated systems for temperature and lighting control. These changes create an energy-conscious setting, making sustainable choices more accessible and convenient [279].
- Information-Based Interventions: Providing users with new information and real-life examples can raise awareness and influence behavior positively [280]. Educational campaigns, energy dashboards displaying real-time consumption data, and personalized energy reports empower occupants to understand their energy usage and identify areas for improvement, encouraging responsible energy practices.
- Gamification: Integrating gamified elements into energy management can motivate users to compete, earn rewards, and achieve energy-saving targets. Leaderboards, challenges, and incentives for reduced energy consumption can foster a sense of achievement and camaraderie, driving sustainable energy habits [281], [282].
- Interventions Based on Monetary Rewards: Offering financial incentives, such as reduced utility bills or rewards for energy-

saving achievements, serves as a powerful motivator [283]. Occupants are incentivized to adopt energy-efficient behaviors to reap the benefits, leading to long-term sustainable actions.

As a starting point for assessing the effectiveness of engagement and behavior change tools, however, it is necessary to verify actual consumption and usage patterns before the intervention. Due to the many variables involved, it is difficult to justify any improvements as a positive consequence of gamification if previous trends in energy consumption and indoor comfort are not clear [284]. For this reason, intelligent control and home automation systems play a vital role: providing real-time data, personalized settings, and convenient control, these systems encourage energy-efficient behaviors, driving positive changes in daily actions and promoting sustainability at home.

Fig. 4.2 The iterative procedure that starts with data collection within the building and returns to the building with the aim of improving its performance. This is achieved both by exploiting the results of data analysis and, in parallel, by promoting user awareness. Adapted from [285]

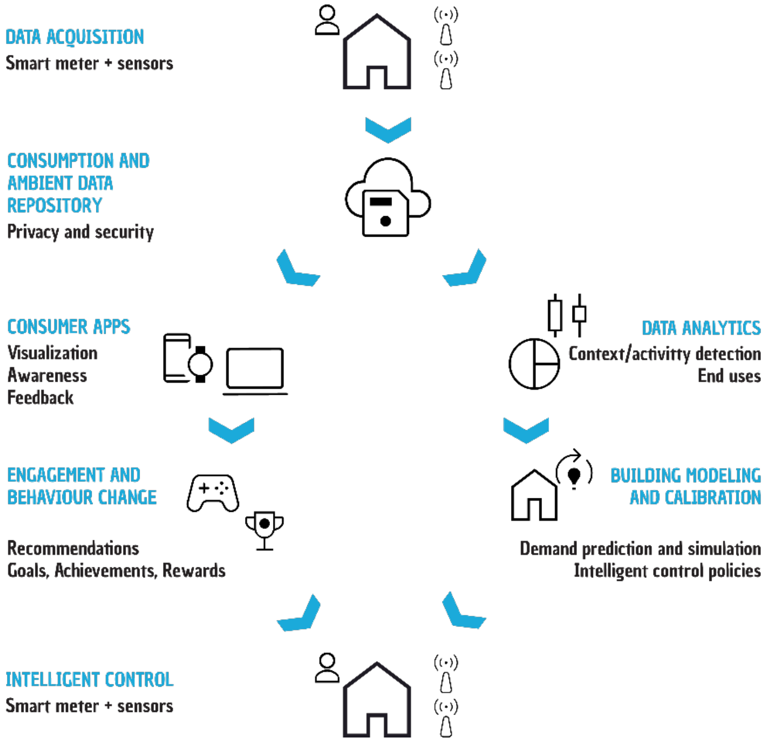


Fig. 4.2, related to the enCOMPASS project [285], perfectly depicts the logical scheme connecting the different phases of the data collection, processing,

analysis and return process, aimed at the intelligent control of the building, even through the same devices and sensors used for monitoring. Building data acquisition should be the basis of a cyclical process that includes data analysis and the creation of the building's digital twin, but also, and more importantly, the provision of data to the user to improve his or her understanding of the building's performance and deter inappropriate behavior. The cycle is completed with intelligent building control, based on the results of data analysis and the real needs and capabilities of the user. Each step in this process involves issues that must be considered before the system is installed, such as privacy and security, user involvement, sensor placement, and data reliability.

The enCOMPASS project is one of the research projects where the interest in understanding the underlying reasons for user behavior is combined with the use of cutting-edge technology. These types of projects provide a valuable set of information and lessons learned that have proven extremely useful for the activities presented in Chapters 5 and 6. Appendix B lists 80 projects that have been identified and selected for their relevance to the topics of energy, comfort, and information for occupants in Smart Buildings. Among the projects that closely align with the discussed topics and from which interesting lessons learned have been gathered, it is worth mentioning those reported in Tab. 4.1. The table provides a brief description of each project, the project end date, and websites where documentation can be accessed.

Tab. 4.1 List of selected EU-funded projects related to the topics of comfort, energy, and smart buildings.

Project acronym and aim	*Project end date*	*Link*
Auto-DAN exploit the evolution of IoT and emerging technologies to capture data and create solutions that will enable the self-optimisation of the building's energy consumption.	30/09/2024	https://cordis.europa.eu/project/id/101000169
BENEFFICE's strategic objective is to reduce wasted energy by incentivizing various consumer types in the wide energy consumer market	30/04/2021	https://cordis.europa.eu/project/id/768774
CLEAR-X project's objective is to help consumers reduce their energy bills by improving the energy performance and comfort of their	29/02/2024	https://cordis.europa.eu/project/id/101033682

homes through the investment in renewable energy and sustainable energy (RES), as well as energy-efficient technologies.		
Cultural-E project define modular and replicable solutions for Plus Energy Buildings (PEBs), accounting for climate and cultural differences, while engaging all key players involved in the building life cycle	30/09/2024	https://cordis.europa.eu/project/id/870072
D^2EPC ambitiously aims to set the grounds for the next generation of dynamic Energy Performance Certificates (EPCs) for buildings	31/08/2023	https://cordis.europa.eu/project/id/892984
enControl-Intuo propose a connected home solution that helps reduce energy costs while preserving comfort for occupants.	30/06/2015	https://cordis.europa.eu/project/id/664165
The main objective of the **EnerGAware** project is to achieve a 15-30% energy consumption and emissions reduction in a social housing pilot and increase the social tenants' understanding and engagement in energy efficiency.	30/04/2018	https://cordis.europa.eu/project/id/649673
The **ENTROPY** aims at the integration between buildings and technologies that facilitate the deployment of innovative energy aware IT ecosystems for motivating end-users' behavioral changes.	30/11/2018	https://cordis.europa.eu/project/id/649849
eTEACHER concept consists of encouraging and enabling energy behaviour change of building users by means of continuous interventions displayed through a set of empower tools to drive informed decisions to save energy and optimise indoor environment quality.	30/06/2021	https://cordis.europa.eu/project/id/768738
FEEdBACk project aims to develop, integrate and trial a wide range of energy focused ICT and behaviour modification applications, that will be used to engage energy users and permit	30/04/2021	https://cordis.europa.eu/project/id/768935

them to understand and change their energy consumption related behaviour.		
inBETWEEN goes beyond currently available ICT technologies used for inducing the end User behaviour change towards more energy efficient lifestyle.	31/10/2020	https://cordis.europa.eu/project/id/768776
The overall aim of **MOBISTYLE** is to raise consumer awareness and awareness of ownership by providing attractive tailor-made combined knowledge services on energy use, indoor environment, health and lifestyle, by ICT-based solutions.	30/06/2020	https://cordis.europa.eu/project/id/723032
OrbEEt proposes an ICT-based framework to induce behaviour change toward energy efficiency by transforming energy measurements into personalized feedback delivered through engaging user interfaces.	28/02/2018	https://cordis.europa.eu/project/id/649753
PEAKapp targets the development of an unprecedented ICT-to-Human ecosystem to trigger lasting energy savings through behavioural change and continuous engagement.	30/06/2019	https://cordis.europa.eu/project/id/695945
SHAPE aim to address association of health, wellbeing, smartness and indoor environmental quality (IEQ) with nearly zero energy buildings (nZEBs)	30/10/2023	https://cordis.europa.eu/project/id/101032267
SMARTeeSTORY will propose an integrated building automation and control systems for monitoring and optimizing building energy performance according to an innovative multi-domain approach.	30/04/2027	https://cordis.europa.eu/project/id/101103956
UtilitEE project focuses on discovering, quantifying and revealing energy-hungry activities and conveys meaningful feedback to engage users into a continuous	30/04/2021	https://cordis.europa.eu/project/id/768600

process of learning and improvement		

Most of the projects listed in the table have concluded and provided a series of lessons learned through documents, reports, and peer-reviewed articles (not specifically mentioned here due to space constraints, but accessible through the provided links on the CORDIS platform). These lessons identify the main challenges to be addressed.

One of the main issues is **maintaining active user engagement over time**. In accordance with the most common practices, there are several possibilities: leveraging social relationships, building communities to share ideas, social activities, crowdsensing, living-labs, web-apps, smartphone apps, co-creation activities or, finally, getting people themselves to act, even combining energy-conscious production and consumption actions. Nevertheless, there is a noticeable absence of an open and well-organized European repository containing behavior change resources, such as educational videos, stories, and questionnaires. The establishment of such a repository would prevent each project on the topic from having to create its own "products" and tools from scratch. It is necessary to ensure a lasting impact after the intervention, working both on the short-term benefits of real-time visualization of energy consumption and measured environmental quality, but also developing continuous awareness through weekly or monthly reports and recommendations. It is therefore recommended to develop longitudinal studies over time (at least 3 years). Other issues concern how to address negative opinions towards gamification or, more generally, technology related to energy usage, and how to make web platforms or consumer apps suitable for a significant percentage of elderly and disabled residents [286] .

An increasingly widespread issue to which everyone is becoming particularly sensitive is that of **privacy** [74]. In this context, it is preferable to encourage the direct exposure of data to users, helping them to understand that monitoring their behavior has the exclusive objective of improving the energy consumption of the environment in which they live and above all the quality and comfort they perceive. Technology is developing new methods of encrypted connection and increasingly unbreakable security keys. However, the availability of a safe and stable connection to the network remains a significant problem even for simple data collection: errors and delays in data transmission and missing or corrupted data can invalidate the evaluation process both before and after the intervention, affecting the involvement of users and thus the validity of the whole project.

The choice and study of the type of users involved is crucial. Agee et al. [265] suggest **pre-identifying specific types of individuals ("personas") to better adapt and customize the implemented monitoring system**. The composition of these "clusters" also impacts the methodology of all studies and the possibility of generalizing the results. Is it better to involve already informed and proactive users or randomly selected users stimulated by awards or publicity? Is it worth involving the administration in the choice or proceeding by stochastic sampling? These choices obviously influence the quality and quantity of the data to be analyzed. People cannot be forced to participate, there is no guarantee that everyone will appreciate these tools, and some resistance to approaching the technology cannot be excluded. Suggestions and proposed actions must consider the specific characteristics of different consumer types and different individual needs. Users know and can only do a certain number of actions, depending not only on their abilities but also on the context in which they live. It is necessary to **design for different motivations**: a person can optimize his or her behavior to reduce the consumption of waste, but also the consumption of water, electricity and the demand for heating or cooling. All possibilities must be ensured, and at the same time the individual must be allowed to focus on one aspect, depending on the sensitivity of the user and what motivates him (money, environmental values, gratification, simple fun, or curiosity). A ready-made, non-customizable tool should not be provided: it may be that one type of data visualization suits one type of person and is not appreciated by another. Does everyone know what a kilowatt-hour is? Or is a smiling emoticon better? An in-depth consideration should be made on how to provide guidance and education: which tools to use? Notifications, reports, rewards? People are often not inclined to spend too much time viewing data or accepting and applying recommendations. **A balance must be found between the quantity and quality of suggestions and the individual's ability to appreciate and apply them**. Furthermore, as the use of these tools can be considered as an energy efficiency intervention, the influence of the so-called "Rebound effect" should be considered: the user, who has high expectations on the energy performance of the building after the energy renovation, changes his habits by increasing energy consumption or leading to energy waste, as he seeks much higher comfort levels based on the high expectations [279]. The interest in maintaining an energy-responsible behavior towards the system may also decrease as the user is satisfied with the obtained small reduction in energy expenditure. Finally, the fact that participants are aware that they are being observed can cause a change in their behavior, which often becomes more socially desirable (Hawthorne effect) [19].

The implementation of IoT systems and technologies, which are not often thoroughly tested before installation, presents a number of technological challenges that further exacerbate these issues. These problems range from sensor selection, positioning, data stability and granularity, to the consistency of information transmission over time. The discussion on these limitations can be found in Chapter 5. In any case, prior to the development of complex indoor technologies, buildings had to align closely with the social context of everyday use. Many times we forget that the majority of constructed buildings (see Section 4.3.2) fall below environmental standards and generally fail to meet user expectations [93]. Technology, along with monitoring, should primarily aim to improve user satisfaction in their living environment by optimizing the understanding and functioning of all building components and features.

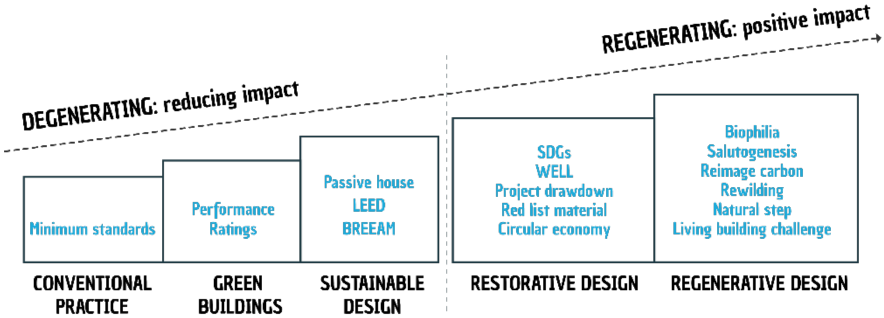
Is it possible to approach building design from a novel standpoint and redefine the ways technology can enhance the interaction between individuals and their living spaces?

4.3.2 Sustainable to Restorative to Salutogenic residential building

When undertaking the design or renovation of a building, various strategies, approaches, and tools can be employed to achieve different levels of environmental consciousness and impact (Fig. 4.3)[287].

Before the widespread adoption of sustainable design, the construction and architecture industry primarily followed conventional practices based on minimum standards. This traditional approach placed a strong emphasis on meeting basic legal requirements, building codes, and safety regulations to ensure the structural integrity and functionality of buildings. While these minimum standards were essential for ensuring the safety of occupants and compliance with the law, they often fell short in addressing broader environmental and social considerations. This conventional practice tended to overlook resource efficiency, environmental impact, and long-term sustainability, resulting in buildings that were not optimized for eco-friendliness and overall sustainability.

Fig. 4.3 From degenerative to regenerative design



However, with growing concerns about climate change and environmental degradation, the concept of green buildings emerged as a transformative alternative. Green buildings sought to bridge the gap between conventional practice and sustainable design by adopting environmentally conscious principles and practices. These eco-friendly structures aimed to reduce their environmental impact through a range of strategies, such as energy-efficient lighting and HVAC systems, the use of renewable energy sources like solar panels, water-efficient fixtures, and the integration of environmentally friendly building materials. The green building movement represented a significant step forward, encouraging a more holistic approach to architecture and construction that considered the entire lifecycle of buildings. It addressed energy and water efficiency, waste reduction, and occupant comfort and well-being.

Soon after, however, sustainable design emerged as the next frontier in the pursuit of a built environment that is truly environmentally and socially responsible. Green building standards, such as LEED and BREEAM, were developed to guide and certify environmentally responsible construction practices. Sustainable design goes beyond the immediate environmental considerations of green buildings by adopting a more comprehensive approach that accounts for the broader impact of buildings on the natural world and society, aiming to create structures that minimize their negative ecological footprint and resource consumption. By incorporating eco-friendly practices such as energy efficiency, renewable energy sources, water conservation, and waste reduction, sustainable buildings aim to maintain ecological balance and conserve resources. Additionally, they often prioritize the well-being of occupants through considerations such as improved indoor air quality and access to natural light.

However, sustainability primarily focuses on reducing harm rather than actively restoring ecological damage [288]. Restorative building design goes a step beyond sustainability by seeking to repair and restore the ecological and environmental damage caused by past development. This approach involves retrofitting existing structures to be more eco-friendly and implementing strategies to rehabilitate nearby landscapes and ecosystems. The central aim is to create "net positive" impact, where the building's operations contribute more benefits to the environment than their environmental footprint. By embracing ecological design principles, restorative buildings strive to create a symbiotic relationship with nature and leave a positive mark on the environment.

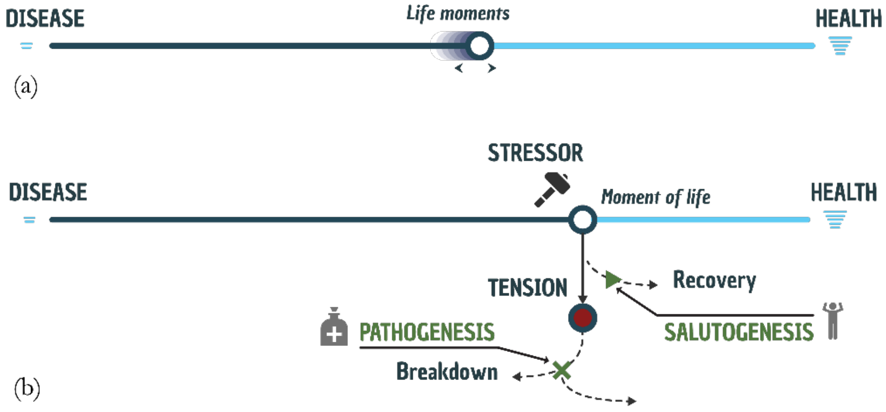
Regenerative building design takes sustainability and restoration to a higher level by actively contributing to the regeneration and enhancement of the ecosystem and community [289]. Going beyond merely reducing harm or restoring ecological balance, regenerative design aims to "do more good" for the environment. It involves integrating ecological systems into the design, fostering biodiversity, enhancing soil health, and promoting ecological resilience. Regenerative buildings are envisioned to become integral parts of the surrounding ecosystems, providing ecosystem services, and benefiting both human and non-human communities. This approach requires a comprehensive and systemic understanding of the interconnectedness between buildings, ecosystems, and communities [237]. Within the broad framework of regenerative design various streams of thought coexist, each contributing unique perspectives on fostering sustainable and harmonious built environments. One such significant approach is salutogenesis, which sets itself apart from practices like rewilding, biophilia, and reimagine carbon. **Salutogenesis places a strong emphasis on human health and well-**

being, adopting a user-centered perspective in its philosophy. By recognizing the pivotal role of human well-being, the salutogenesis approach seeks to create built environments that actively contribute to enhancing occupants' physical, mental, and emotional welfare [290]. This comprehensive focus on health aligns seamlessly with the overarching goal of regenerative design, which aims to create spaces that are not only ecologically restorative but also deeply supportive and nurturing for the people who inhabit them. By intertwining the principles of salutogenesis with regenerative design, a powerful synergy emerges, fostering a symbiotic relationship between human flourishing and the regeneration of the natural world [291].

In a broader perspective, salutogenesis theory, developed by Aaron Antonovsky [292], is a conceptual framework that provides a new viewpoint on understanding health and well-being. In contrast to pathogenesis, which focuses on the causes and treatment of diseases and illnesses [293], salutogenesis concentrates on the origins and maintenance of health, aiming to identify factors that promote positive health outcomes and resilience in individuals and communities [294].

Antonovsky conceptualized health as a continuous journey along an axis, stretching from complete illness (dis-ease) to full well-being (ease). As people, in our daily lives, within the environment we experience every day, we are not all well and occasionally fall ill, but we are all on a continuum with different degrees of health [295] (Fig. 4.4a).

Fig. 4.4 a) Salutogenic disease-health continuum; b) Salutogenic and pathogenic approaches compared in stressor and tension management



But what makes people sick and what makes people healthy, specifically in the built environment? Simplifying an extremely broader concept, life experience exposes us to stresses and stressors that often turn into tensions [296]. The pathogenic approach prioritizes disease prevention and treatment, addressing specific illness-causing agents and symptoms proactively before tension leads to a breakdown. In contrast, the salutogenic approach focuses on identifying and nurturing factors that enhance health and well-being, emphasizing an individual's ability to cope with stressors through an ongoing process that transcends pathogenic agents. In the presence of tension, this approach triggers a semi-automatic process of recovery (Fig. 4.4b).

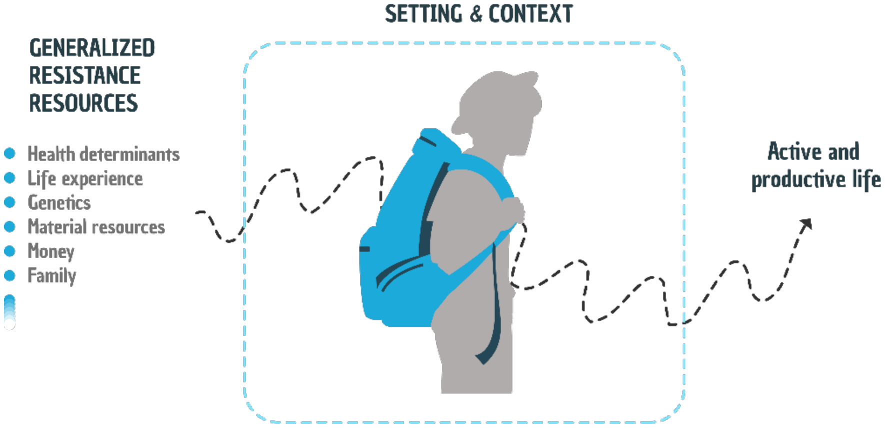
Central to the salutogenic model is the concept of the "Sense of Coherence" (SOC) [294], [297], [298], which Antonovsky introduced as a key psychological factor influencing an individual's ability to cope with stressors and maintain good health. SOC comprises three main components:

- Comprehensibility: This aspect refers to a person's perception of whether the stimuli and events in their life are understandable, structured, and predictable. A higher level of comprehensibility allows individuals to make sense of their experiences, reducing feelings of confusion and uncertainty.
- Manageability: This component reflects a person's belief in their ability to handle and cope with life's challenges effectively. A strong sense of manageability empowers individuals to take appropriate actions and utilize available resources to address stressors and maintain well-being.
- Meaningfulness: This dimension involves perceiving life as meaningful and worthwhile. When individuals find purpose and significance in their experiences and values, it enhances their motivation and commitment to taking care of their health.

Antonovsky posited that individuals with a strong sense of coherence are more likely to adopt health-promoting behaviors, cope positively with stress, and experience better overall health outcomes. In the salutogenic model he emphasizes the role of "Generalized Resistance Resources" (GRRs) [294] in fostering resilience and enhancing SOC. GRRs are a set of internal and external resources that individuals can draw upon during times of stress. These resources can include social support, coping skills, self-esteem, educational opportunities, and access to healthcare services, but also a home, private property, and money – everything that help us cope with stressors, becoming salutary factors that actively promote health. The availability and utilization of GRRs contribute to the development and reinforcement of a SOC.

To better grasp the concept of SOC and GRRs, we can imagine a hiking backpack filled not just with essentials but brimming with various resources that help navigate life's challenges. In this allegory, we can envision this "Antifragile Salutogenic Backpack" as a mountain trekker's survival kit (Fig. 4.5). Antifragile, as described by Taleb [299], means systems or entities not only withstand shocks and uncertainty but also benefit and improve from them. It goes beyond resilience, embracing volatility as an opportunity for growth and adaptation. In an antifragile system, just like in the salutogenic approach, disruptions act as a catalyst for positive evolution, resulting in increased strength, robustness, and better adaptation to thrive in an unpredictable world. The Antifragile Backpack contains an array of GRRs, **providing individuals with the ability to proactively address stressors and unexpected hurdles**. As more resources are added to this backpack, one's SOC strengthens acting as a compass to navigate life's twists and turns.

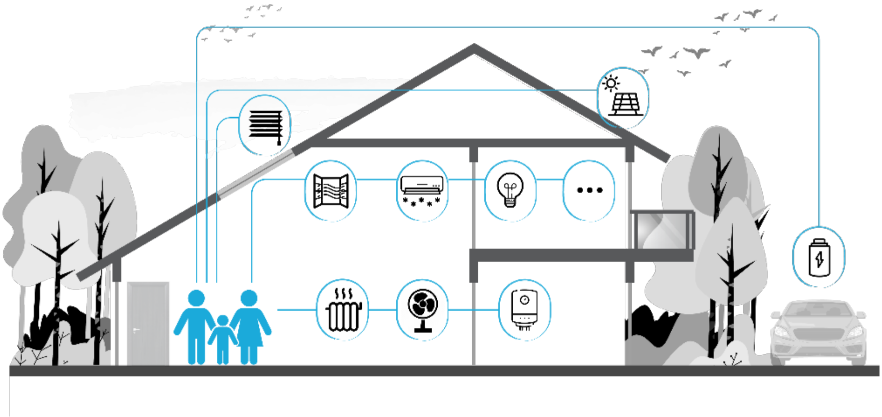
Fig. 4.5 "Antifragile Salutogenic Backpack" of generalized resistance resources



Drawing an analogy to the built environment, incorporating well-being into the design and operation of buildings represents a novel approach that is still evolving. While a single, definitive definition remains elusive, a diverse range of perspectives, guiding principles, and operational practices has emerged, offering effective support for considering well-being in architectural endeavors [43]. An essential starting point for designers is to fulfill occupants' fundamental needs at the base of Maslow's hierarchy [300], like breathing, eating, and drinking. However, the real challenge lies in transcending mere "comfort" and crafting environments that elevate experiences to higher levels of enjoyment, love, self-esteem, and creativity. How can designers go beyond the essential and create spaces that nurture and inspire human flourishing? This requires a comprehensive understanding of the interplay between physical, psychological, and social factors in the built environment, fostering a harmonious fusion of functionality, aesthetics, and meaningful experiences. As this pioneering approach continues to evolve, the built environment becomes an exciting canvas for architects to explore and redefine the boundaries of well-being in the pursuit of a more holistically fulfilling human experience.

Regenerative environments research pays particular attention to the residential context [301], recognizing that people spend a significant portion of their daily lives in their homes. This focus often involves comparing the regenerative qualities of natural settings, such as green or blue spaces, with urban environments in close proximity to residences [302]. Numerous studies [303]–[306] examine the potential links between nearby nature and improved health outcomes, including self-reported health, reduced risk of psychiatric disorders, and lower all-cause mortality rates [307]. Moreover, the concept of regeneration in the residential context extends beyond contact with nature [308]. Some research explores how specific architectural characteristics in densely built urban areas can contribute to the regenerative experience [290]. These factors may involve elements that enhance well-being and promote relaxation. At the heart of the residential context lies, however, its multifaceted role in people's lives. **The home itself becomes a collection of resources** (See Section 4.3.3), like the objects in the " Antifragile Salutogenic Backpack", which users should be able to access and use conveniently to meet their needs and enhance their living experience (Fig. 4.6). Homes serve a dual purpose: as a sanctuary where individuals seek refuge from the outside world, engage in activities that fulfill psychological and social needs, and find a sense of security and continuity; and also, as a place to rejuvenate physical and cognitive resources, so that returning home after a tiring day becomes a salutogenic path to recovery.

Fig. 4.6 Home and its resources



4.3.3 Building resources

We discussed the salutogenic backpack and its analogy with the building. But what resources should the building have?

According to Lollini et al. [237], technological regenerative solutions can be defined as multifunctional highly adaptive systems, where the physical separator between the interior and exterior environment can change both its functions and its features and behavior over time, in response to transient performance requirements and boundary conditions. The aim is to improve the overall building performance, protect people from hazards, and help them access essential resources such as food, water, and shelter. These functions can only be achieved by integrating technologies for the different sub-systems of the building, including the building envelope, interior elements, building services, and controls. Tab. 4.2 presents several technical solutions mentioned in [237], which are grouped into the three main building systems: building envelope, interior elements and finishes, and active systems (Heating, Ventilation, and Air Conditioning (HVAC), renewable energy systems (RES), and controls).

Tab. 4.2 Regenerative solutions according to [237]

Building envelope	*Interior elements and finishes*	*Active systems*
Green wall	Green wall	Ventilation with heat recovery
Green roof	Water wall/Fountain	Ventilator with heat recovery integrated in window frame

High-tech shading systems	Natural Materials	Air inlet through green façade
Operable windows	Photocatalytic coating	Fresh air preheating earth duct air
Smart opaque envelope	Recycled material	Automatic operable windows
Double skin facades	Internal shading devices	Turbine ventilation fan
Photocatalytic envelope system	Solar Shelf	Night cooling
Straw bale building envelope	Sound-absorbing 3d-printed panels	Building Management Systems
Acoustic, façade panel with micro-drilling	Antibacterial TiO2 coating and Responsive Coatings	Seed oil fuelled CHP
Insulation materials ecologically, toxicologically certified	Insulating materials with ecological and toxicological certification	Bio-hydrogen energy
Prefab, straw bale façade	Interior wall/ceiling coverage	Smart digital ceiling
Thermally activated glass façade	Daylight provision by a sunlight redirection system with heliostats and fixed mirrors	PV with hydrogen storage + heat pump - 100% RES house
High thermal insulation thickness		
Regenerative PCM-Facades	Atrium with plants and natural elements	Direct current of solar panels within the building
Solar tube and or shed window	Interior partitions with plasterboards capable of absorbing contaminants	High temperature solar panels for heating & cooling
Wind tower, directional chimney		
Solar Greenhouse		
Rammed-earth façade elements	Use of natural sounds and murals inspired by nature	Sound masking solutions

The actual condition of the housing stock, however, makes the implementation of such solutions highly complicated, as they are expensive, often incompatible with existing buildings, and, as indicated by the authors of the cited report, more suitable for office buildings.

Referring to Europe, some issues must be considered:

- Many buildings are old and likely fail to meet basic living standards. One-third of the housing stock in Denmark, Belgium, and the United

Kingdom was constructed prior to 1946. Approximately 45-50% of the housing stock in Germany, the Baltic Member States, Greece, Hungary, Finland, and Sweden was built between 1946 and 1980, while this proportion rises to 50-60% in Italy, Slovakia, Bulgaria, and Romania [309]. The age of the buildings makes the implementation of modern solutions challenging, considering their incompatibility.

- While the age of buildings is undoubtedly a factor, the most critical aspect to address is the lack of proper maintenance. Unfortunately, maintenance is often neglected due to the absence of immediate benefits and the high associated costs. Around 15% of the EU population lived in homes with a leaking roof, impacting their quality of life. Additionally, 6.9% of the EU population struggled to keep their homes adequately warm in 2021, with the highest shares observed in Bulgaria, Lithuania, Cyprus, and Greece, and the lowest in Finland, Slovenia, Sweden, and Austria. Moreover, 1.5% of the EU population lacked a toilet, shower, and bath, with the highest percentages in Romania, Bulgaria, Latvia, and Lithuania [310].
- Rising house prices and rents make the cost of housing burdensome for many. The housing cost overburden rate, which indicates the share of the population living in households where housing costs represent over 40% of disposable income, was 10.4% in EU cities and 6.2% in rural areas in 2021 [310]. While solutions may be available to improve the situation, their implementation is often hindered by their complexity and high costs. As a result, achieving substantial and widespread change becomes challenging and elusive.

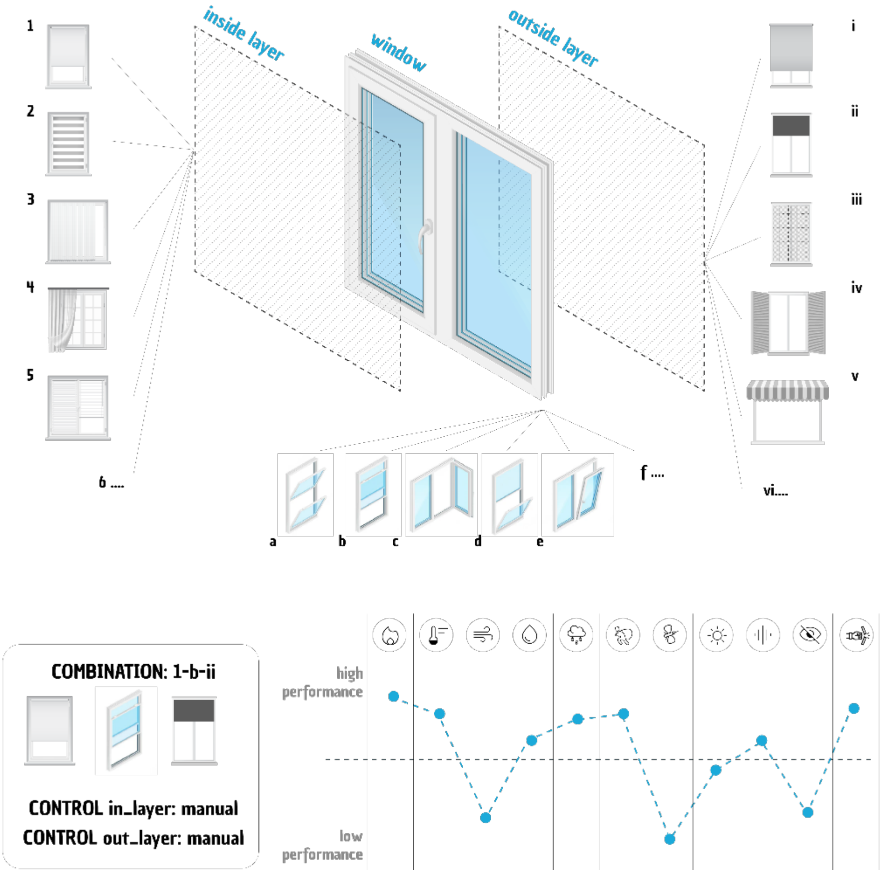
Beyond economic considerations, top-down or legally imposed solutions risk not aligning with the genuine primary preferences of occupants. Often, these solutions are not fully understood, and sometimes the functioning of a specific installed component, whether it is related to systems or the building envelope, remains unclear, leading to inefficiencies. Comfort and individual's perception in a personal residential environment are subjective (See Section 1.1.1 and 2.1): some people prefer to keep windows open in the summer rather than using air conditioning, others prefer a blanket and lower room temperature instead of adjusting the thermostat, and lighting preferences differ, with some favoring diffuse lighting over spotlights. Even noise preferences vary, with some individuals preferring a noisy atmosphere, while others prefer a quiet area. **To help create these flexible environments, the building must become our strongest ally**, transcending mere aesthetic considerations. Considering this vast existing building stock and the limited percentage of new constructions [309], the current state of buildings must be the starting point, enhancing usability with preferably small, non-invasive modifications to maximize effectiveness. **The focus should be on re-evaluating the existing resources and guiding users towards more conscious and informed utilization**.

As an example, consider a resource commonly found in buildings: the window (Fig. 4.7).

Fig. 4.7 Building resources: the window

The main requirements of a window, in addition to durability and maintainability, include resistance (to fire, wind, impact, water), safety (for people and objects, ensuring privacy, etc.) and environmental wellbeing (lighting, thermal and acoustic insulation, air tightness, view to the outside, etc.). The window, including any shade components that may be added from the inside or the outside, may be designed and used in an almost unlimited number of ways. Each combination can be assessed during the design phase through multi-objective simulations, also utilizing online tools [311], or during its use through monitoring or user feedback, to determine its compliance to the mentioned requirements (Fig. 4.8). This evaluation also considers the operating mode and the type of control (manual or automatic) selected by the user. Achieving high performance is possible simply by modifying the chosen combination, where some changes (e.g. changes to how and when the window is opened, or adjustments to shading elements) may not entail additional costs. However, for this to be practical, the possibilities offered by the resource, in this case the window, must be evident to users, simplifying its use when it is not easily exploited.

Fig. 4.8 Window components and requirements optimization



The window is just one of the available resources found in a residential building, which, following the classification in Tab. 4.2, can be grouped into 3 categories: Building envelope, Interior elements and finishes, Active systems (Tab. 4.3).

Tab. 4.3 Residential building resources

Building envelope	*Interior elements and finishes*	*Active systems*
External walls	Green wall	Heating Boiler
Roofs	Water wall/Fountain	Hot water Boiler
Floors	Natural Materials	Air inlets
Shading systems	Internal shading devices	Sound masking solutions
Operable windows	Recycled material	PV
Doors	Solar Shelves	Solar panels
Indoor partitions	Interior wall/ceiling coverage	Night cooling
Sunspaces	Mirrors	Ventilation fan
Terraces	Natural elements	AC unit
Stairs	Any appliances	Ventilation with heat recovery
Elevators	Any equipment	Heat Pump
	Occupants	Night cooling
	Music	
	Sound masking solutions	Building Management Systems
	Use of natural sounds and murals inspired by nature	Voice Controlled Home Automation System
…	…	…

The goal is to create a building that adapts to the user's preferences, choices, and habits. Not a passive house, designed according to top-down standards, nor an adaptive house where flexibility becomes the active or automatic ability to adjust to different changes or circumstances, but an **adaptable building that can be modified or adjusted by someone or something to suit a specific purpose or context** – a "*resourcient*" ("resources" + "efficient") building, equipped with a multitude of resources. The focus is on human well-being, placing the individual at the center, as they can choose and act on various aspects and components of the building, with automation as an optional support if desired.

Determining the Key Performance Indicators (KPIs) to define whether a house is "*resourcient*" is crucial and an open question: the factors outlined in

Section 3.3 remain highly relevant and ensure excellent performances. When dealing with indicators, however, there is a risk of reducing everything to acceptable ranges or levels and designing with the sole aim of achieving those abstract numbers, often distant from expressing the occupant's true level of satisfaction. In a salutogenic approach, the building, like humans, may not need to reach fixed stages determined by predefined values of physical and environmental parameters. It can also accept transitioning to a temporary stage that is not "perfect" [312] - even negative or not calibrated according to preference statistics - because the user may and should face what is unfamiliar, endure conflicts, and grow stronger through this confrontation (salutogenic heterostasis [293]). Indicators only come into play at the end of this cycle, acting as a validation of the project. Validation, being linked to user satisfaction, can only depend on the user's subjective judgement. Therefore, the performance indicator cannot simply be a value linked to a physical parameter (temperature, lux, noise level, etc.), but more likely an evaluation on a scale of perceptions or preferences that may vary from person to person, even within the same space. The user can also feel satisfied on an objective level, such as in terms of energy consumption or energy bills.

The most critical indicator should, however, measure the number of available resources in and around the building, their ease of use, and their ability to act on multiple levels and senses. The question that naturally arises is: How do we then approach the design process? **What KPIs do we base our decisions on**? Attempting to refine the design parameter (e.g., choosing between PMV or adaptive comfort, UDI or sDA, etc.) can be limiting in some cases and too site-specific. It may well be better to consider sDA for one case study, UGR for another, or even create a new additional parameter for yet another scenario. By thinking differently and genuinely placing the user at the center, **the task of a designer is to ensure that the occupants of the space can access multiple tools rapidly and intuitively to modify the surrounding environment according to their desires**. If users are presented with a variety of possible actions and a salutogenic backpack of resources to draw from, they can, if properly informed, decide how to use them and what values of physical parameters to "set" to achieve their well-being.

In this context, the **IoT** and ICT tools holds immense potential [313], not as an artificial intelligence that turns our homes into autonomous entities, but **as**

an additional tool to access the GGRs and the building resources. It serves as a technology that lists and highlights these resources, providing insights into their advantages, disadvantages, beneficial impacts, and consumption patterns. Moreover, it offers personalized recommendations on which resources to leverage and makes them readily available to us. Rather than being a complex network of sensors, wires, gateways, and servers, IoT must seamlessly integrates with the existing smart devices, voice assistants, sensors, and actuators that we already trust and find useful in our homes, transforming our homes into convenient and versatile devices that can be used and experienced according to our preferences and needs. Its functionality extends beyond merely controlling and regulating devices. Instead, it aids us in understanding the impact of our actions, the energy consumption of our household appliances, and helps improve the overall healthiness of our living environments while minimizing costs. By providing valuable insights and actionable data, this technology empowers us to make informed decisions, optimize resource utilization, and create a more regenerative and salutogenic living space.

4.4 Concluding remarks

To optimize the performance of a residential building, it is essential to optimize the relationship between occupants and the building, ensuring their well-being. Each home is a personal world, and every user has their unique way of living within it. Therefore, using data from standard monitoring systems becomes challenging when they fail to adapt to these individual circumstances. Big data must be part of a broader concept of the building, which can be seen as a collection of resources available to the user. Data help users to better understand these resources, while IoT facilitates their utilization by automating processes or suggesting best practices.

5 Development of a low-cost, plug-and-play and open-source monitoring and automation system: MOQA

> *"Technology is at its best when it is invisible."*
>
> NASSIM NICHOLAS TALEB

5.1 Background and aim

Traditionally, strategies for diagnosing IEQ in buildings were very invasive and often involved on-site interventions [314]. In recent years, however, helped by the publication of specific standards [315], [316], a brand-new class of sensors has developed from the BMS industry to continuously monitor IEQ using pervasive and inexpensive autonomous systems installed in all occupied areas of the building [317]. Hayat et al. [230] provide an excellent overview of environmental sensing and monitoring in buildings, outlined in Fig. 5.1.

Fig. 5.1 Overview of sensing and environmental monitoring in buildings

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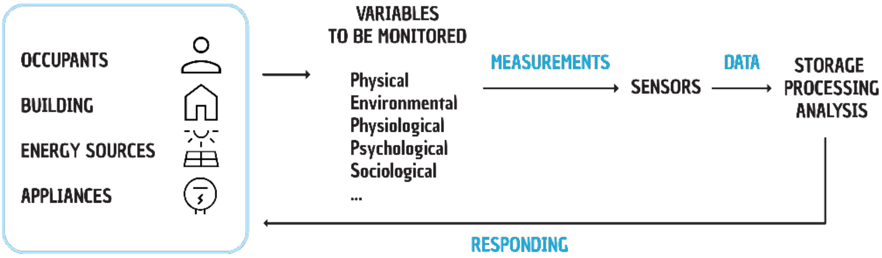
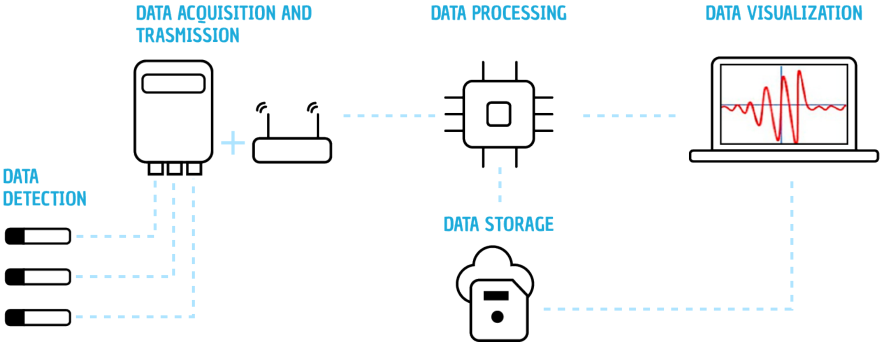


The building has several components or appliances that directly affect its performance, as well as the actions of the user who lives in it. These aspects can be schematized into variables, which can be measured by sensors. The information collected is sent, to be stored and constantly monitored, to a processor that, eventually, can respond and communicate back to the building.

To go into a little more detail, the core of the system begins with sensing devices, which are responsible for collecting data from the environment. After the sensors capture environmental data, a data acquisition component comes into play, typically including a data logger responsible for data collection and initial tasks such as data sampling and analog-to-digital conversion. Once the data is collected and prepared, it needs to be transmitted to a central processing unit or storage system. This is where the communication gateway steps in. The gateway ensures that data is sent reliably and can aggregate information from multiple sensors or data loggers before transmission. It includes a communication module that manages the data transmission, using technologies like Wi-Fi, cellular networks, or other wired or wireless methods. The central processing unit is the brain of the system. It receives the data sent by the gateway and performs additional processing. This may include data fusion, analysis, and potentially real-time decision-making based on predefined algorithms. The CPU also manages control logic, which can determine when and what data to collect, ensuring efficient operation. Collected data needs a home for storage and organization. This is typically achieved through a database, where data is structured and stored for historical analysis. To make the system accessible and user-friendly, a human-machine interface (HMI) can be added. It provides a graphical user interface or web-based dashboard through which users can interact with the system, allowing real-time data visualization, report generation, and configuration of system settings.

Fig. 5.2 Schematic of a monitoring system



To keep the system running, a reliable power supply is essential. The choice of power source can vary depending on the deployment location and may encompass mains electricity, batteries, or even solar panels, all aimed at ensuring uninterrupted operation (Fig. 5.2).

Since 1980's [318], monitoring systems have been miniaturized and their cost has been considerably reduced: this makes it feasible to gather information from various sources and realize simple settings that do not always require the intervention of an expert. Within the current literature [314] [319] two primary solutions have gained prominence. The first solution encompasses the integration of sensors, gateways, and a processor into a toolbox or toolkit (type A). Thanks to recent advancements in miniaturization, it is now entirely feasible to seamlessly incorporate all the aforementioned components of a monitoring system onto a single microcontroller. This integration enables the consolidation of various functions, including data acquisition from a diverse array of sensors, data logging, communication, data processing, and even the implementation of a user interface, either through a mobile application or the creation of a web page accessible to the microcontroller. In the second solution, depending on the size of the area to be monitored, one or more gateways with or without a controller are set up, and the sensors, leveraging wired or wireless communication systems, are distributed throughout the space to get a more comprehensive overview of the environment. (type B). In both cases, data are stored either by transferring them directly to the cloud and/or locally, in most cases, via Secure Digital (SD) or MicroSD cards.

Tab. 5.1 below presents a selection of recent articles that have been examined and discuss the development or of low-cost indoor environmental monitoring systems, classified according to the two categories listed above. The research covered articles published after 2016 given how much technology has improved in recent years. Only those systems capable of simultaneously monitoring multiple aspects of IEQ (thermal, visual, acoustic, air quality) are considered. Since sensor technology is now widely accessible and employed in different sectors, the table cannot be considered exhaustive. However, it is useful for understanding the main objectives, challenges, and gaps.

Tab. 5.1 Selection of reviewed publications published in recent years (2016-2023).

Ref	*Type*	*Main Hardware*	*Measured variables*	*Real-time data visualization*	*Key features and limitations*
[320]	A	Arduino Pro Mini	T, UR, CO_2, occupant motion, 1surface temperature, light intensity	No	- The toolkit includes a single, replaceable sensor, allowing measurement of one variable at a time. - A transistor is present for powering off the sensor and SD storage, minimizing idle current draw. - The system is open-source, with documentation provided, but requires non-standard expertise for recreation.
[321]	B	Raspberry Pi2	T, UR, CO_2, CO, NO_2, O_3, SO_2, Cl_2	Through IoT Web Server	- The system hardware consists of a series of sensor nodes, measuring all listed variables, and gateways. - Sensor nodes and gateways communicate wirelessly via Zigbee, making the system scalable and expandable in space. - Data from the gateway is sent both to a microSD for local storage and an IoT web server. The Emoncms IoT application is used for posting collected data. - To save energy, the end devices of the system have a sleep mode.
[322]	A	ESP32	T, UR, CO_2, $PM_{2.5}$, sound pressure level, illuminance	Through IoT Web Server – only researchers allowed – and	- Off-the-shelf sensors and smart home sensors from major retailers are used simultaneously. - Real-time feedback from users is also collected. - While the system currently appears as a bulky toolkit, it has the potential to be divided into multiple components capable of intercommunication. The ThingSpeak IoT application is used for posting collected data.

				real-time monitors	
[323]	A	Arduino Mega	T, UR, globe temperature, CO_2, dust, sound pressure level, air velocity, occupant presence, illuminance	Real-time monitor	- It's a portable toolkit in a prototypical form, with measurements closely tied to its placement. - It collects user feedback on the environment while simultaneously measuring various environmental parameters.
[324]	B	Raspberry Pi3	Equipment power and energy consumption	Through mobile application	- The system arises from the need to raise user awareness and, therefore, offers a low-cost, simple client interface. - It can be scaled and expanded to include additional variables but is currently limited to measuring only electrical consumption using current clamps.
[325]	A	Arduino Uno and Raspberry Pi2	T, UR, CO_2, CO, NO_2, $P1M_{2.5}$, PM_{10}	No	- An experimental toolkit that collects data only locally and doesn't provide a visualization platform for end-users. - Built with low-power components, it doesn't optimize its overall size, which is not extremely compact.
[326]	A	Proprietary hardware: the architecture is developed based on	T, UR, CO_2, $PM_{2.5}$, sound pressure level, illuminance	Through web and mobile application	- Equipped with 3G and 4G connectivity, it's more easily transportable and installable in a wider range of environments, including those without internet access. - It concurrently gathers user feedback on IEQ - It features a web and mobile interface for data visualization, along with user-friendly suggestions.

		the software-as-a-service concept			
[327]	A	Arduino Uno	T, UR, CO_2, $PM_{2.5}$, TVOC, air velocity, globe temperature, occupancy, illuminance	No	- Originally designed as a stand-alone toolkit, multiple toolkits can be easily integrated to create a Type B monitoring system. - The toolbox uses the open-source, agent-based software platform VOLTTRON for data communication and analysis. However, there's no online platform for remote control. - Not all sensors in the toolkit are low-cost; priority was given to accuracy.
[328]	A	ESP32	T, UR, air velocity, globe temperature	Through IoT Web Server – only raw data	- It's open-source, easy to build, fully documented on Github, reliable, and can be self-calibrated by the user. However, it still requires some expertise for assembly and configuration. - Attention has also been given to the product's aesthetic qualities. - It's prepared to accommodate a 4G connectivity module in the next version.
[329]	A	Raspberry Pi2	T, UR, CO_2, TVOC	No	- Primarily intended for measuring air quality in hospital environments. The system is still in the prototype phase.
[330]	B	ESP8266	T, UR, CO_2, barometric pressure, window/door state	Real-time OLED display	- An open-source tool that allows freedom in developing equipment to meet specific needs. - Potentially aimed at informing various stakeholders, including tenants, building technicians, energy managers, researchers, and policy developers.
[331]	A	Arduino Mega	T, UR, CO_2, $PM_{2.5}$, TVOC, air velocity,	Through IoT Web Server	- A very compact tool suitable for measuring IEQ, especially in work environments. It conveniently fits on a workstation. - The Blynk IoT application is used for posting collected data.

			globe temperature, barometric pressure, sound pressure level, illuminance		
[332]	A	hardware solution	T, UR, CO$_2$, CO, TVOC, formaldehyde, air velocity, globe temperature, sound pressure level, illuminance	Through IoT Web Server	- Originally designed as a stand-alone toolkit, multiple toolkits can be easily integrated to create a Type B monitoring system. - The product's aesthetic aspect is meticulously designed, resembling a commercial product ready for the average consumer. It conveniently fits, for example, on a workstation. - It calculates indices in a clear and actionable format for building owners, facility managers, tenants, and occupants, displaying them on the web platform.
[333]	B	Non-specified PSoC microcontroller	T, UR, CO$_2$	Through IoT Web Server	- The system can cover long distances while simultaneously monitoring multiple rooms. It is particularly designed for monitoring educational environments. - It relies on the online data platform EnControl for data visualization.
[334]	A	Raspberry Pi3	T, UR, CO$_2$, CO, PM$_{2.5}$, benzene, formaldehyde, sound pressure level, illuminance	Through IoT Web Server – only researchers allowed – and	- The system is a smart sensor box that includes all sensors and a display for measurement visualization. - Despite its do-it-yourself nature, the smart box appears as a finished product that is easily installable.

				real-time display	
[335]	A	STM32	T, UR, CO_2, O_2, TVOC,	Through web and mobile application	- The system utilizes an unusual and rather unique feature – it uses electromagnetic interference-free bidirectional visible light communication technology. - Sensing data from the smart sensor tag and command data for requesting environmental sensing data are transmitted bidirectionally between the base station included in the lighting system and the smart sensor tag by modulating them into the light emitted by LED lamps.
[336]	A	Non-specified PSoC microcontroller	T, UR, CO_2, CO, TVOC, $PM_{2.5}$, PM_{10}, sound pressure level, illuminance	Real-time display	- It's one of the few examples that operates on rechargeable batteries, making it completely independent of the electrical grid. - Its costs are very low, even lower than those of sensors available on commercial retailers. - It presents itself as a smart box, delivering user-friendly information through easily understandable indices, although it doesn't collect feedback from occupants.
[337]	A	Arduino Pro Mini	T, UR, CO_2, $PM_{2.5}$, PM_{10}, occupancy	Through IoT Web Server	- The system is well-documented on Github and can be easily reconstructed. - The enclosure, aesthetically curated, was designed by product development students and engineering students. - Primarily designed for school environments. Special attention is given to noise and disturbances created by continuous operation to avoid disturbing students.

Low-cost is the present and the future. All the examined papers aim at making systems affordable, considering that the accuracy of sensors- which has reached satisfactory levels - is now less important than the possibility of obtaining a long-term characterization of the IEQ variability [317]. Low-cost means being able to make increasingly miniaturized and less invasive monitoring systems, but more importantly, more spaces can be monitored for the same budget, expanding knowledge about the performance of indoor environments.

An additional concept that is frequently mentioned is "plug-and-play". In many cases it means having an easily transportable toolkit that is configured prior to installation and simply needs to be connected to electricity. In the case of Tiele et al. [336], the system even runs on a battery that provides 60 hours of operation without connection or recharging. Many of these systems, in fact, demonstrate a keen focus on their power consumption [320], [321], [325], [335], [336], seeking to reduce it through the implementation of sleep modes or by optimizing sensor operation from the outset. Most of the monitoring systems presented are based on open-source hardware and software, mainly Arduino and Raspberry [321], [323]–[325], [327], [329], [331], [334], [337], [338], which proves to be an extremely valuable means of expanding access to knowledge and know-how of low-cost, easy-to-build products [339]. However, there is a risk of proliferation of disparate systems that, despite having clear documentation for replication [320], [328], [337], struggle to gain traction in the market, particularly among operators and households. This divergence detracts from the ultimate goal: the broad adoption of these systems to truly enhance indoor environmental quality and reduce energy consumption.

The monitored variables often align with established standards, focusing on specific aspects of a building's performance, such as temperature, humidity, air quality, and occupancy. What's less common is the simultaneous monitoring of IEQ alongside energy consumption or electrical data for individual appliances or the entire building. Low-cost technology capable of achieving this integration is available, as detailed in Fulk et al. [324], which includes solutions like smart sockets, current clamps, beyond more complex Building Automation and Control Systems (BACS).

However, in most of the research presented, the perspective is that of the researcher or space manager, rather than that of the occupant [14], [265]. Often, the plug-and-play system falls short of its benefits because users are unable to relocate the toolkit, or in the event of a power failure, the system may not restart automatically or without expert intervention. Users are primarily engaged to provide feedback on IEQ [322], [323], [326], but the level of user-system interaction and satisfaction is not thoroughly investigated. Data collected is seldom directly accessible to end-users, and the intricate information is rarely translated into user-friendly language, making it less comprehensible to the general public. Furthermore, with low-cost systems like the ones described, the collected data does not "get back" to the building or occupants who cannot directly benefit from automation or suggestions based on the monitoring data analysis. Currently, this capability is only possible with more complex and expensive BACS [340], or alternatively, with Voice Controlled Home Automation Systems (VCHAS), which, as discussed in Section 3.4, have yet to find wide application in research. Despite the uncertainty surrounding IEQ and the parameters to be measured [14], there is a lot of literature that can help researchers build their own conclusions and suggestions to support the development of a monitoring and automation system (see Section 3.3).

A monitoring system that possesses flexibility, supports different communication protocols, and can easily scale by accommodating a variable number of measurement points and parameters for monitoring, not only IEQ parameters, represents the solution to address the inherent uncertainty associated with the concept of indoor living quality. However, the abundance of available IoT communication protocols [244], [314], [341] should not result in solution fragmentation. The following paragraphs, along with Section 6, detail the monitoring and automation system, MOQA, developed during the PhD program and its application in different contexts. Information from Chapter 2, 3 and 4 played a pivotal role in defining what aspects to monitor and the tools to employ. This led to the choice of a VHACS, exploring its potential in environmental energy behaviour research for buildings. The product's design and configuration include the following key features:

- It is a low-cost system that utilizes smart-home sensor technology, making it affordable and accessible.

- The system is plug-and-play, allowing end-users to easily set it up and use it without any technical expertise or complications.
- It supports multiple communication protocols, enabling seamless integration with various devices and systems. It also offers flexibility for expansion or contraction based on specific needs.
- It concurrently tracks multiple parameters, extending beyond IEQ to encompass energy consumption and more. The system isn't reliant on pre-established specific sensors, prioritizing interoperability among diverse measurement systems and focuses on transforming devices into smart components that elevate indoor living quality.
- The system is built on an open-source code, which is already widely shared within the online community. This facilitates implementation on different platforms and encourages collaboration and innovation.
- It is user-centred, meaning it can be customized and tailored to meet the specific requirements and preferences of individual users.
- Many of its components are readily available in the market and familiar to users, not exclusively for enthusiastic makers or technicians.
- Privacy of the occupants is a priority, ensuring that their personal information and data remain secure and protected.
- The system not only collects monitoring data but also utilizes that information to provide suggestions or implement automated actions directly within the system. It establishes direct communication channels with both the user and various building components, enabling efficient and effective management of the monitored environment.

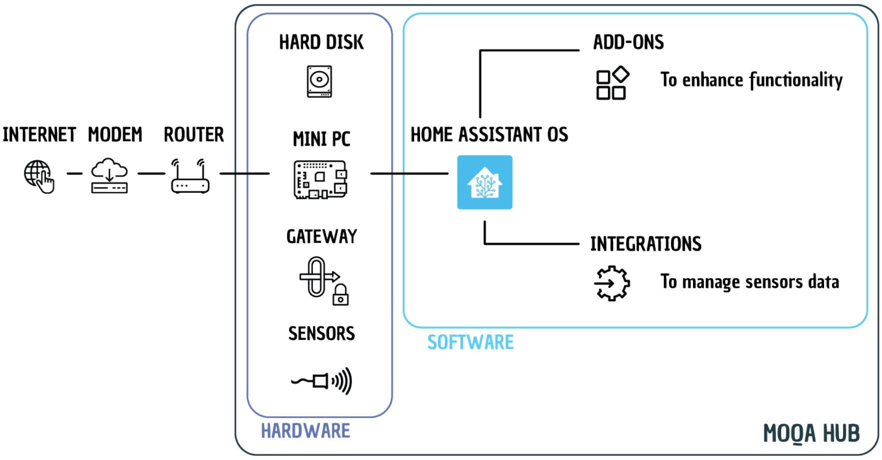
Overall, the product is designed to be cost-effective, user-friendly, adaptable, and privacy-conscious, while also leveraging monitoring data to improve the building's performance and enhance the user experience.

The methodological approach to product development went beyond literature analysis. Recognizing the technological nature of the product, the development process aimed to thoroughly understand its advantages and disadvantages by starting from scratch. This involved addressing all phases of product implementation, including writing the code, creating a prototype, and conducting field testing. In this regard, valuable insights were gained through direct comparisons with startups operating in the same domain within the Italian and European territory. This interaction provided significant hints and guidance throughout the product development process.

5.2 MOQA architecture

Fig. 5.3 illustrates the general architecture of the MOQA system. Its core is built upon the Home Assistant operating system (Section 5.2.1) running on a mini-PC capable of connecting to several sensors and devices (Section 5.2.2), via different gateways (Section 5.2.3). The operating system manages data collection and processing (Section 5.2.4) and offers a visualization interface for monitoring, alerting, and automation (Section 5.2.5). All these components are enclosed within a meticulously designed and constructed case (Section 5.2.6).

Fig. 5.3 MOQA system architecture.

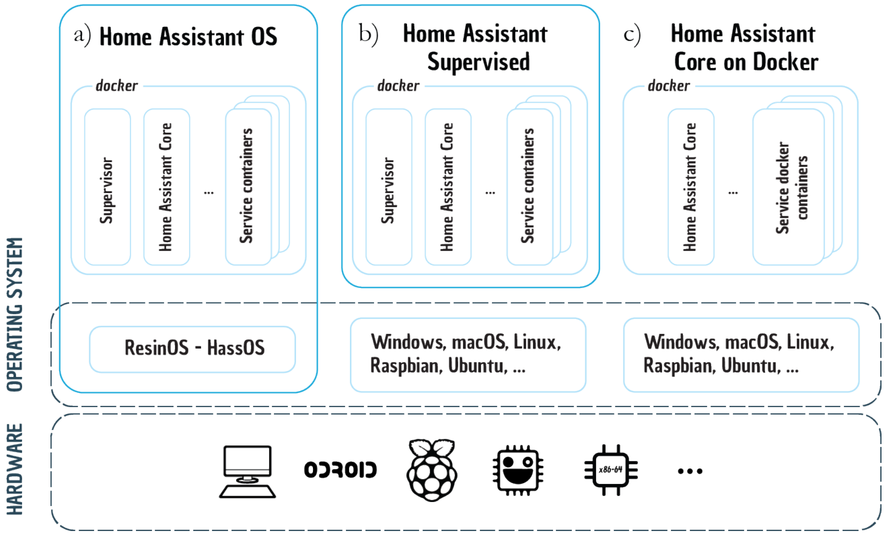


5.2.1 Core of the system

MOQA architecture matches that of a typical smart home hub. As outlined in Section 3.4, several similar solutions already exist and, therefore, the decision was made to leverage existing work and available architectures rather than building one from scratch. This was made feasible by utilizing the open-source code from many of these platforms, particularly that of Home Assistant.

Home Assistant (HA) [250] is an open-source home automation platform that can be installed on virtually any computer or micro/mini-computer. It enables the creation of a central hub through which various home automation services and components (actuators, sensors, devices, Internet services, etc.) can interact. This facilitates their systematic, centralized, and automated management, even when they are based on different technologies and brands. As mentioned, Home Assistant can be run on a variety of computing platforms, including those with Windows, macOS, or Linux operating systems, as well as on low-cost, low-power micro/mini-computers such as Mini PCs, Raspberry Pi or Odroid, and even on Network-Attached Storage (NAS) devices [342]. The easiest way is to use the official Home Assistant Operating System (Home Assistant OS) which is built on top of ResinOS. This is a lightweight Linux-based operating system that is optimized for running Home Assistant and its associated add-on. In this configuration, known as Home Assistant OS (Fig. 5.4a), the Graphical User Interface is also pre-installed, facilitating the customization of the platform through add-ons and integrations.

Fig. 5.4 Home Assistant different installation packages.



The other way to run Home Assistant is by installing it on another operating system, such as Ubuntu or Raspbian (configuration Home Assistant Supervised package). This requires manually installing dependencies, and add-on through Docker, a containerization platform that enables the packaging and distribution of software applications and their dependencies in isolated, portable containers, and configuring the system to run Home Assistant (Fig. 5.4b). Another way is running it in a virtual environment such as a virtual machine or on a cloud service like AWS, GCP, or Azure, where both Home Assistant Core code and additional components can be installed through Docker (Fig. 5.4c). This is useful if you want to separate your Home Assistant instance from your main operating system, or if you want to take advantage of the scalability and reliability offered by cloud services. In any case, all the options will require an initial setup, configuring the system and adding devices, automations, and customization according to user's needs.

Home Assistant offers several methods for integrating components and services. The quickest approach is auto-discovery, which notifies the user of automatically detected components within their environment, allowing the user to configure these components into the hub through a guided procedure. In cases where components are not auto detected, they can be integrated using the web interface or through configuration files. The integration of components and services involves creating entities on the hub, which can vary in type depending on the nature of the integration and represent logical elements corresponding to the functionalities of what has been integrated. For instance, when integrating a smart bulb a "Light" entity is created. This entity has a state (typically, on/off) and properties (such as brightness, color, etc.). Entities can be queried (to check, for example, whether a light is on or off) and controlled. To "control" them means to invoke the services related to them to change their state (for example, calling the service "*light.turn_on*" to turn on a light). This "invoking of services" can be done through both the graphical interface (clicking on the bulb to turn it on effectively invokes the service "*light.turn_on*") and through more structured, even automatic procedures, as well as through voice commands via smart speakers. Various techniques, known as "integrations", exist for integrating non-domotic components as well, such as traditional air conditioners, fans, old security systems, and so forth. Every home automation Hub, such as HA, offers remarkable versatility in automating the behavior of integrated components and services, fostering effective collaboration among diverse entities and services through "add-ons". HA is also equipped with a built-in smartphone application that not only facilitates the remote administration of one's home automation but also leverages GPS location services to trigger automations and more.

With an active online developer community and a well-established track record, Home Assistant is one of the most robust smart home platforms: failures are infrequent, typically arising only from user errors during manual configuration. It is also the platform with the most proven high attention to user privacy: being an open-source software, its source code is available to anyone, making any malicious behaviors easily detectable. All personal data, encompassing GPS locations, entity states, automations, manual actions, and more, is locally stored at the HUB, ensuring that no information is disclosed to third parties. Additionally, its releases are signed by CodeNotary.

In summary, the primary reasons for selecting Home Assistant as the core of MOQA are as follows:

- HA is a widely adopted open-source system within the smart home domain, boasting a large online community of developers and users. This extensive network ensures continuous system updates, stability, and provides valuable insights.
- HA prioritizes privacy by keeping data local, offering end-to-end encryption for remote access, and providing user control over data sharing. It does not rely only on cloud services and users have the flexibility to choose which integrations and devices to connect.
- HA allows for the integration of both professionally validated sensors and off-the-shelf or DIY sensors. This approach ensures data accuracy while making it more accessible and understandable to users who are familiar with commercially available technologies.
- HA provides comprehensive access to raw measurement data and offers a high degree of customization for integrations, components, user interfaces, and automation.

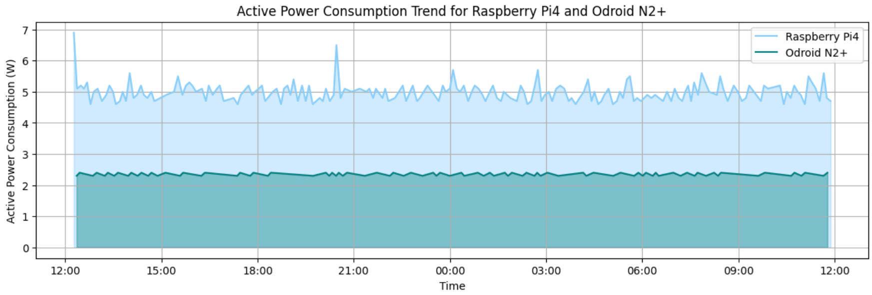
It is precisely the flexibility the key advantage of this application, enabling the seamless modification of hardware and sensors (Section 5.2.2), communication protocols (Section 5.2.3), and data collection methods (Section 5.2.4) to best suit the specific case study.

5.2.2 Main hardware and sensors selection

The selection of the main hardware for the MOQA smart home hub, designed to monitor and automate IEQ, was a pivotal decision in the research phase. Initially, the Raspberry Pi 4 was chosen for its widespread use and proven stability, making it a staple in the realm of smart home solutions. MOQA's system architecture was particularly well-suited to the Raspberry Pi's capabilities, allowing Home Assistant to run smoothly and efficiently. However, the landscape of technology is ever-shifting, and the Raspberry Pi 4 soon became difficult to procure due to a crisis in the technology market that led to increased prices and scarcity. This unforeseen challenge prompted a pivot to an alternative hardware – the Odroid N2+. The transition to the Odroid N2+ was not only a testament to the adaptability of the MOQA system but also revealed the hardware's impressive stability and functionality. Despite the Odroid N2+'s lack of an onboard Wi-Fi module – a stark contrast to the Raspberry Pi 4 which supports wireless connectivity – the ethernet requirement proved advantageous. During intensive monitoring campaigns, an ethernet connection is often preferable for its consistent and reliable data transfer rates, ensuring that the MOQA system could maintain uninterrupted data acquisition, which is crucial for accurate IEQ monitoring and automation.

The dual hardware option available for MOQA provided a unique opportunity to evaluate the electric consumption of two distinct devices, offering insights into the energy expenditure of such monitoring systems. The paradox of employing energy-intensive tools to reduce a building's energy consumption is counterproductive; if the devices designed to enhance efficiency themselves consume significant amounts of power, the ultimate goal of energy conservation is compromised. In the case of the Raspberry Pi 4, while running Home Assistant or similar services, its power consumption varies significantly depending on the specific model and operational load, typically ranging from 2.7W to 6.4W. These fluctuations in energy usage are critical to document, as they directly affect the overall energy efficiency of the monitoring system. On the other hand, the Odroid-N2+'s use of the big.LITTLE processor architecture showcases a commitment to power efficiency, with its consumption ranging from 1.6W to 6.2W. This range is also influenced by the workload but tends to skew towards the lower end compared to the Raspberry Pi 4. Moreover, the Odroid-N2+'s implementation of DDR4 RAM is notable for its power-saving benefits over the LPDDR4 SDRAM found in the Raspberry Pi 4, further contributing to its more efficient energy profile. The chart below (Fig. 5.5) illustrates the electrical consumption of two identical MOQA prototypes – one equipped with a Raspberry Pi and the other with an Odroid N2+ – monitored over the span of a full day using a Zigbee Aqara smart plug. The Raspberry Pi4 consumed approximately 0.117 kWh of energy, while the Odroid N2+ consumed roughly 0.055 kWh. This results in a difference of 0.063 kWh, indicating that the Odroid N2+ consumed less energy than the Raspberry Pi4 during the recorded period. To put this into perspective, assuming an energy cost of €0.30 per kWh, over the course of a year, MOQA with the Raspberry Pi4 would incur an energy cost of around €12.8, whereas MOQA with the Odroid N2+ would only cost approximately €6.6. This represents nearly half the energy cost, showcasing the cost-effectiveness of using the Odroid N2+ in terms of energy consumption. The MOQA project consciously avoided the transition to an embedded system design with bespoke circuit board assemblies (PCBA), a path that could have led to reduced costs and enabled scalable manufacturing. This decision was made to preserve the open-source integrity of the tool, ensuring that it could be freely distributed and used in a variety of settings, both academic and commercial.

Fig. 5.5 MOQA main hardware active power consumption



Another foundational characteristic of MOQA is its configuration as a smart hub capable of aggregating diverse sensors, devices and data sources, extending beyond just environmental factors, rather than merely functioning as a sensor box. This aspect of MOQA is crucially supported by the selection of Home Assistant as its central platform (see Section 5.2.1). **MOQA does not require the use of specific sensors but instead opens to the use of multiple technologies and monitoring methods**. Concerning IEQ, energy consumption, and the general parameters defined in section 3.3, MOQA adopts a pragmatic approach towards the performance requirements of the integrated sensors. Instead of aiming for laboratory-grade measurement precision, which is more suited for diagnostic and forensic applications, MOQA targets "good-enough" big data[10]. This approach allows for significant reductions in both hardware costs and operational expenses, as it eliminates the need for technical personnel for IEQ data acquisition. This strategy is in line with the recommendations made by literature [228], [343], which advocate for the use of inexpensive, accurate, and readily available devices. These devices must strike a delicate balance between cost-effectiveness and scientific validity, particularly in high-performance building applications. While it is acknowledged that low-cost sensors for temperature and humidity can nowadays achieve excellent accuracy, as demonstrated among others by Demanega et al. [338], challenges remain with other sensor types. For instance, low-cost sensors have shown substantial under-reporting of particulate matter (up to 50%), acceptable CO2 response levels within a 15% range, and inconsistent results when measuring volatile organic compounds. These findings underscore the significant potential of this technology for indoor monitoring applications. However, they also highlight the need for ongoing refinement and improvement.

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[10] Considering the advent of new technologies and environmental measurement methods now widely available on the market (from smartphone applications to sensors easily purchasable on major retail sites) there is a need to distinguish between what can be defined as "citizen data" (data that citizens generate and gather typically outside the domain of scientific research, using a broad range of monitoring technologies and techniques) and "research data" [386]. The term "just good enough data" is used in the literature to discuss how citizen-generated data can create alternative methods of developing, valuing, and interpreting datasets [387]. This concept refers to data produced through low-tech and low-cost instruments, as well as observational or experiential data (including "eyes on the ground" data), which can be utilized to generate different narratives and forms of evidence for addressing environmental issues. Citizen data might not adhere to the typical validation and legitimation practices that define scientific data (which also has its own criteria for determining if data is sufficient). Nonetheless, it might be adequate to initiate discussions with environmental regulators, make claims about polluting activities, or advocate for increased investment in regulatory-standard monitoring infrastructure. Such "just good enough" citizen data could also contribute to diverse data practices and narratives, fostering more open and democratic engagement with environmental data and issues [388].

In addition to cost and accuracy, other factors considered when selecting sensors for MOQA included performance metrics (such as range, sensitivity, resolution, and calibration stability), power specifications (including supply voltage, supply current, portability, and battery-powered or mains-powered options, as well as battery-less sensors), output formats (analog or digital), interface protocols, and physical form factors. MOQA’s design philosophy, overall, is not just about harnessing current technology but also about recognizing and addressing its limitations to enhance the system's overall effectiveness in monitoring and improving indoor environments.

The tables below serve as a comprehensive reference for a range of low-cost sensors, directly integrable with Home Assistant and MOQA, detailing costs, features, and integration capabilities. They are a useful tool for those constructing a monitoring hub like MOQA or for those interested in standalone sensors for monitoring specific environmental variables that can provide quick data and insights independently.

Tab. 5.2 Comparison of Low-Cost IEQ Sensors - Prices and Monitored Parameters

	Price @10/23 [US$]	*PM2.5*	*PM10*	*VOCs*	*CO_2*	*CO*	*O_3*	*Temperature*	*Humidity*	*Pressure*	*Sound Level*	*Light Sensor*
Air mentor	240	Yes	No	Yes	Yes	No	No	Yes	Yes	No	No	No
AirBeam3	249	Yes	No	No	No	No	No	Yes	Yes	No	No	No
AirLink Davis	215	Yes	Yes	No	No	No	No	Yes	Yes	No	No	No
air-Q basic	399	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No
Airthings View Plus	299	Yes	No	Yes	Yes	No	No	Yes	Yes	Yes	No	No
Airthings Wave	199	No	No	No	No	No	No	Yes	Yes	No	No	No
Airthings Wave mini	80	No	No	Yes	No	No	No	Yes	Yes	No	No	No
Airthings Wave Plus	230	No	No	Yes	Yes	No	No	Yes	Yes	Yes	No	No
airthinx IAQ	699	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No	No
Amazon Air Quality Monitor	60	Yes	No	Yes	No	Yes	No	Yes	Yes	No	No	No
Aranet4 Home	180	No	No	No	Yes	No	No	Yes	Yes	Yes	No	No
Atmotube Plus	99	No	No	Yes	No	No	No	Yes	Yes	Yes	No	No

Atmotube Pro	189	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	No	No
AWAIR Element	149	Yes	No	Yes	Yes	No	No	Yes	Yes	No	Yes	Yes
Awair Omni	499	Yes	No	Yes	Yes	No	No	Yes	Yes	No	Yes	Yes
Eve Room	105	No	No	Yes	No	No	No	Yes	Yes	No	No	No
Fybra Home	290	No	No	Yes	Yes	No	No	Yes	Yes	No	No	No
Honeywell Air Quality Monitor	189	Yes	-	Yes	Yes	No	No	Yes	Yes	No	No	No
IQAir AirVisual Pro	340	Yes	Yes	No	Yes	No	No	Yes	Yes	No	No	No
Kaiterra Sensedge Mini	400	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	No	No
LaserEgg 2 Chemical	-	Yes	Yes	Yes	No	No	No	Yes	Yes	No	No	No
LaserEgg 2 CO2	-	Yes	Yes	No	Yes	No	No	Yes	Yes	No	No	No
Netatmo Weather Station	200	No	No	No	Yes	No	No	Yes	Yes	Yes	Yes	No
NuWave Sensor cair	168	Yes	Yes	Yes	No	No	No	Yes	Yes	No	No	No

Plume Labs Flow 2	199	Yes	Yes	Yes	No	No	No	Yes	Yes	No	No	No
PurpleAir Touch	199	Yes	No	Yes	No	No	No	Yes	Yes	Yes	No	No
Rubix POD	-	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes	Yes	Yes
SPARROW	249	No	No	No	No	Yes	No	Yes	Yes	No	No	No
uHoo	299	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
uRAD Monitor A3	499	Yes	No	Yes	Yes	No	No	Yes	Yes	Yes	Yes	No
Wynd Air Quality Tracker	79	Yes	Yes	No	No	No	No	No	No	No	No	No
Wynd Halo	149	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes	Yes
Xiaomi Mi PM2.5 Detector	79	Yes	No	No	No	No	No	No	No	No	No	Yes
Xiaomi Youpin Qingping	50	Yes	Yes	No	Yes	No	No	Yes	Yes	No	No	No

Tab. 5.3 Comparison of Low-Cost IEQ Sensors - Other parameters

	Wearable	*Smart home integrations*	*iOS / Android*	*WiFi*	*Bluetooth*	*LED Indicator /Display*	*API*	*Website*
Air mentor	Portable	No	Yes	Yes	Yes	LED	-	https://informapuae.com/air-mentor/
AirBeam3	Portable	No	Yes	Yes	Yes	No	Yes	https://www.habitatmap.org/blog/airbeam3-technical-specifications-operation-performance
AirLink Davis	No	No	Yes	Yes	No	No	-	https://www.davisinstruments.com/products/airlink-professional-air-quality-monitor
air-Q basic	No	No	Yes	Yes	No	LEDs	Yes	https://shop.air-q.com/air-Q-basic-air-analyser-11-sensors
Airthings View Plus	Portable	Alexa/IFTTT/Google	Yes	Yes	Yes	e-ink 2.9”	Yes	https://www.airthings.com/en/view-plus
Airthings Wave	Portable	Alexa/IFTTT/Google	Yes	Yes	Yes	LED Ring	Yes	https://www.airthings.com/wave
Airthings Wave mini	Portable	Alexa/IFTTT/Google	Yes	Yes	Yes	LED	Yes	https://www.airthings.com/wave-mini
Airthings Wave Plus	Portable	Alexa/IFTTT/Google	Yes	Yes	Yes	LED Ring	Yes	https://airthings.com/wave-plus/
airthinx IAQ	No	Nest	Yes	Yes	Yes	LED	Yes	https://airthinx.io/iaq/

Amazon Air Quality Monitor	Portable	Alexa	Yes	Yes	No	LED	No	https://www.amazon.it/amazon-smart-air-quality-monitor-conosci-la-qualita-dell%E2%80%99aria/dp/B08X2V3T2B
Aranet4 Home	Portable	No	Yes	No	Yes	e-ink	Yes	https://aranet4.com
Atmotube Plus	Portable	-	Yes	No	Yes	RGB LED		https://atmotube.com
Atmotube Pro	Portable	-	Yes	No	Yes	RGB LED		https://atmotube.com
AWAIR Element	No	IFTTT/Alexa/Google Home	Yes	Yes	Yes	LED matrix	Yes	https://getawair.com/products/awair-2nd-edition
Awair Omni	No	IFTTT/Alexa/Google Home	Yes	Yes	Yes	LED	Yes	https://www.getawair.com/products/omni
Eve Room	No	HomeKit	Yes	No	Yes	e-ink	No	https://www.evehome.com/en/eve-room
Fybra Home	No	No	Yes	Yes	No	LED	No	https://fybra.co/en/fybra-home/
Honeywell Air Quality Monitor	Portable	-	Yes	Yes	No	OLED touch screen	-	https://sensing.honeywell.com/lp/honeywell-air-quality-monitor#getInTouch
IQAir AirVisual Pro	Portable	SMB/IFTTT	Yes	Yes	No	Display 5”	Yes	https://www.iqair.com/air-quality-monitors/airvisual-series
Kaiterra Sensedge Mini	No	IFTTT/Alexa/Google Home	Yes	Yes	No	No		https://www.kaiterra.com/sensedge-mini

LaserEgg 2 Chemical	Portable	HomeKit IFTTT	Yes	Yes	No	Display 2.6”	No	https://kaiterra.com/products/laser-egg-2-plus/
LaserEgg 2+ CO2	Portable	HomeKit IFTTT	Yes	Yes	No	Display 2.6”	No	https://www.kaiterra.com/en/laser-egg-co2
Netatmo Weather Station	No	IFTTT HomeKit	Yes	Yes	No	LED	Yes	https://www.netatmo.com/
NuWave Sensor cair	No	IFTTT/Alexa/HomeConnect	Yes	Yes	No	LED	No	https://www.cairsensors.com/index.html
Plume Labs Flow 2	Yes	-	Yes	No	Yes	12 RGB LEDs	Yes	https://plumelabs.com/en/
PurpleAir Touch	No	No	iOS	Yes	No	LED	Yes	http://www.aqmd.gov/aq-spec/product/purpleair-pa-i-indoor
Rubix POD	No	No	No	Yes	No	No	Yes	https://www.lkb.pl/files/pdf/aparatura/monitorowanie_powietrza/rubix_pod_en.pdf
SPARROW	Yes	No	Yes	No	Yes	LED	-	https://www.sparrowsense.com
uHoo	No	IFTTT/Alexa/Google Home	Yes	Yes	No	LED	No	https://getuhoo.com/home
uRAD Monitor A3	No	No	No	Yes	No	LED	Yes	https://www.uradmonitor.com/uradmonitor-model-a3/
Wynd Air Quality Tracker	Wearable	Honeywell Home, Alexa,	Yes	No	Yes	LED	-	https://www.amazon.com/Introducing-Amazon-Smart-Quality-Monitor/dp/B08W8KS8D3

		Google Home						
Wynd Halo	Portable	Honeywell Home, Alexa, Google Home	Yes	Yes	No	LED ring + LCD	-	https://shop.hellowynd.com/collections/products/products/wynd-halo-smart-air-monitor
Xiaomi Mi PM2.5 Detector	Portable	No	Yes	Yes	No	OLED Display	No	https://www.spanningglobal.com/product/original-xiaomi-smartmi-air-detector-mini-pm2-5-portable-sensitive-air-quality-monitor/
Xiaomi Youpin Qingping	Portable	HomeKit	Yes	Yes	-	OLED Display	No	https://en.xiaomitoday.it/xiaomi-launches-qingping-air-detector-the-gadget-that-analyzes-the-air-quality-of-your-home.html

As mentioned, the versatility of MOQA in assimilating a variety of data sources extends beyond environmental variables. In a specific case study referenced in Section 6.5, data from Apple Watches were integrated using the Cozie app – an iOS application for collecting environmental quality satisfaction and physiological data – developed by Tartarini et al.[344]. Integration methods and the corresponding code are accessible in Appendix C. Additionally, the study included real-time electricity pricing data for energy consumption calculations of electrical devices by linking to a constantly updated online Excel sheet from ARERA, the Italian Regulatory Authority for Energy (see Appendix C). These examples highlight MOQA's capability to gather different information types, enriching the knowledge base of the monitored building and user comfort while also providing user-friendly dashboard visualizations, such as translating energy parameters from kWh to euros.

5.2.3 Network and communication

Smart home communication protocols enable machines to effectively interact with each other and form a unified network. A smart home protocol is an agreed-upon format of exchanging data between devices that enables the development of different distributed systems for complete automation. These protocols allow for compatibility, interoperability, extensibility, and security across multiple platforms, enabling machine-to-machine communications in homes or businesses. The most popular industry standards for these protocols include:

- Zigbee: a wireless communication protocol that is based on the IEEE 802.15.4 standard. It is designed to be low-cost, low-power, and low-bandwidth. Pros: low power consumption, low cost, secure, mesh network topology. Cons: limited range, can be affected by interference from other wireless devices.
- Z-Wave: another wireless communication protocol that is designed for home automation. It is similar to Zigbee in that it is low-power and low-bandwidth. Pros: Low power consumption, secure, good range. Cons: Limited number of supported devices.
- Bluetooth: a short-range wireless communication protocol that is commonly used for connecting devices such as smartphones, laptops,

and speakers. Pros: high compatibility, easy to setup, low energy consumption. Cons: short range, can be affected by interference from other wireless devices.

- Wi-Fi: a wireless communication protocol that is commonly used for connecting devices to the internet. Pros: High bandwidth, easy to setup, wide compatibility. Cons: High power consumption, can be affected by interference from other wireless devices, require a stable internet connection.
- Thread: a low-power mesh networking protocol designed to be used in home automation and IoT devices. It uses IPv6 networking to provide reliable, low-power mesh networking for devices in and around the home. Pros: low power consumption, secure, easy to set up. Cons: Limited range, limited number of supported devices.
- Infrared (IR): a line-of-sight wireless communication protocol that is commonly used for controlling devices such as televisions and air conditioners. Pros: no need for a hub, easy to set up, low cost. Cons: Line of sight communication only, remote batteries can run out quickly.

The market is experiencing significant growth, and new protocols are emerging and spreading in domestic environments. In particular, it is worth mentioning:

- Matter protocol: an open-source wireless communication protocol developed by the Connected Home over IP working group, which is led by Amazon, Google and Apple, designed to be a standard for connecting smart devices in a home. Similar to Zigbee and Z-Wave, Matter is based on the Internet Protocol (IP) and it uses Wi-Fi and Ethernet for communication. Pros: High bandwidth, easy to set up, wide compatibility, provide interoperability between different vendors smart home devices. Cons: requires a stable internet connection, still emerging technology.
- LoRaWAN is a media access control (MAC) protocol designed for low-power wireless sensor networks and the Internet of Things (IoT) devices. It uses the unlicensed spectrum, specifically the sub-gigahertz frequencies that are less crowded, to establish a secure, low-power, and wide-range wireless network. It operates on a star-of-stars

topology where gateways, which are connected to the internet, act as gatekeepers to the devices communicating on the network. The main advantages of LoRaWAN are:

- Long range: it can reach up to 15 km in rural areas and up to 2 km in urban areas;
- Low power consumption: it is designed for battery-powered devices and sensors, which means it can operate for years on a single battery;
- Security: it offers secure, bi-directional communication, with support for over-the-air device activation and secure over-the-air updates;
- Scalability: it is designed to support a large number of devices, as well as to handle high traffic and large data payloads.

The main disadvantage is that it has a relatively low data rate and it is not suitable for high-bandwidth applications like streaming video.

To integrate a data source or a sensor into MOQA, it is necessary to first identify its communication protocol and then install or connect the specific gateway. After that, adjustments must be made to the system's configuration file, commonly referred to as "configuration.yaml", specifying the data source type, name and all relevant parameters. An alternative, more straightforward integration method through a graphical interface is also available: when the gateway is installed, the data source or sensor can be automatically recognized by the operating system, which guides toward its easy connection that enable data transferring. The procedure is contingent on the specific data source and is closely tied to the sensor communication protocol.

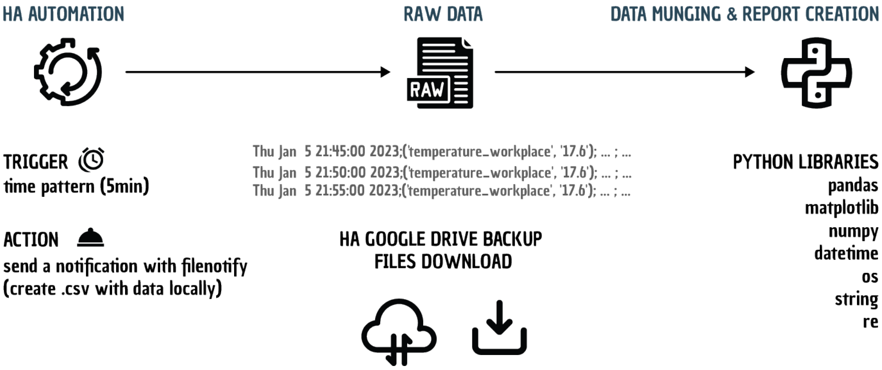
MOQA has undergone testing in various case studies, primarily utilizing Zigbee, Z-Wave, Bluetooth, and Wi-Fi protocols. An ongoing trial is exploring the use of the LoRaWAN protocol, which is more effective for covering extensive distances and measuring environmental parameters that extend beyond indoor or immediate building surroundings. To date, using Wi-Fi and Bluetooth sensors is feasible by directly leveraging the typically pre-installed Wi-Fi and Bluetooth modules on the main hardware (mini-PC). The use of alternative protocols requires the addition of dongles or gateways, which, to enhance system flexibility, have always been connected externally to the PC via USB ports, at the expense of solutions and modules integrated directly on the motherboard.

5.2.4 Data storage

Home Assistant offers different database solutions to store data, such as MySQL, SQLite, or PostgreSQL. It can also utilize NoSQL databases like MongoDB and MariaDB, especially useful for handling timeseries data. Data can be stored locally on a device running Home Assistant or remotely in a cloud-based database such as InfluxDB or Graphite, both popular choices for home automation.

In the vast majority of the implemented MOQA case studies, a different data storage approach was required, as it was more convenient to utilize raw data for generating weekly reports. Leveraging the functionalities of Home Assistant, time-triggered automations were created to query the sensors every 5 minutes and record the monitored value in a CSV file. This file was simultaneously stored locally on the Raspberry Pi and linked to the backup system on Google Drive, thereby preventing potential data loss resulting from network connection interruptions. Subsequently, a data analysis script was developed using Google Colab and Python, directly linked to the files to automatically generate and download the monitoring report at regular fixed intervals, incorporating relevant graphs and statistical analysis (Fig. 5.6).

Fig. 5.6 MOQA data collection and storage flow



```
Thu Jan  5 21:45:00 2023;('temperature_workplace', '17.6'); ... ; ...
Thu Jan  5 21:50:00 2023;('temperature_workplace', '17.6'); ... ; ...
Thu Jan  5 21:55:00 2023;('temperature_workplace', '17.6'); ... ; ...
```

The impact of the correct database configuration for data storage on the performance of Home Assistant and MOQA is significant. In fact, if the operating system is installed on a storage medium unsuitable for multiple overwrites, such as a microSD card, it can lead to system crashes. In the default configuration, the system retains all data for 10 days. However, it is possible, through the proper configuration of the "Recorder" component (https://www.home-assistant.io/integrations/recorder/), to modify this time limit or, in general, substantially mitigate the adverse effects of excessive data storage by selecting the specific entities of interest. An additional contribution is provided by the history-explorer-card add-on (https://github.com/alexarch21/history-explorer-card), which can be installed via HACS. This add-on has the capability to display and download data even beyond the default 10-day limit, using hourly statistics (average, minimum, maximum) for tracking the trends of the values of the sensor entities with measurements or the sensor entities that feature values integrated over time. These long-term statistics differ from other objects in the Home Assistant database, which are stored chronologically and automatically purged after a set period. Statistics are never purged because they are summarized on an hourly basis, resulting in only 24 entries per day.

5.2.5 Dashboard design

Once data are organized within a database, they are primed for analysis, visualization, and utilization in automations or optimizations. A user-centered approach, as detailed in Section 4.3.1, underscores the importance of the data visualization interface, emphasizing that data should not only be accessible but also comprehensible, usable, and actionable. According to Aghajan et al. [345], effective strategies to enhance end-user engagement with smart home platforms can be categorized into:

- Quality of interaction (e.g. speed, brevity/easiness);
- Information efficiency (e.g. accuracy and completeness);
- Usability (e.g. ease of use, intuitiveness, user satisfaction);
- Aesthetics;
- Functionality (e.g. offered features);
- Acceptability (e.g. cost-effectiveness, user base)

The design of the data visualization dashboard in MOQA was also significantly influenced by research findings [274], [280], [346]–[351] indicating that energy data visualization can profoundly affect users' understanding of a building's energy profile and foster a more inclusive approach to building management.

To deepen the understanding of user needs and enhance the dashboard's effectiveness, semi-structured interviews and surveys were implemented during a 6-month monitoring campaign at the UniTrento Fablab, a university-based digital fabrication workshop and innovation hub. Throughout this period, indoor environmental quality and the electrical consumption of five lab machines were closely monitored. The real-time data collection and display aimed to increase awareness among users about the importance of environmental sustainability and the reduction of energy consumption in educational lab settings. The ongoing monitoring has provided a unique opportunity to iteratively refine the user visualization interface, benefiting from the high volume of feedback from the diverse group of individuals engaged with the lab. This feedback was instrumental in making step-by-step improvements to ensure that the dashboard was not only informative but also user-friendly and tailored to encourage proactive interaction with the data.

Semi-structured interviews and questionnaires were employed as a primary method for gathering user feedback. Initial questions to establish context, followed by specific questions on version 1 of the dashboard (shown in Fig. 5.7) were proposed.

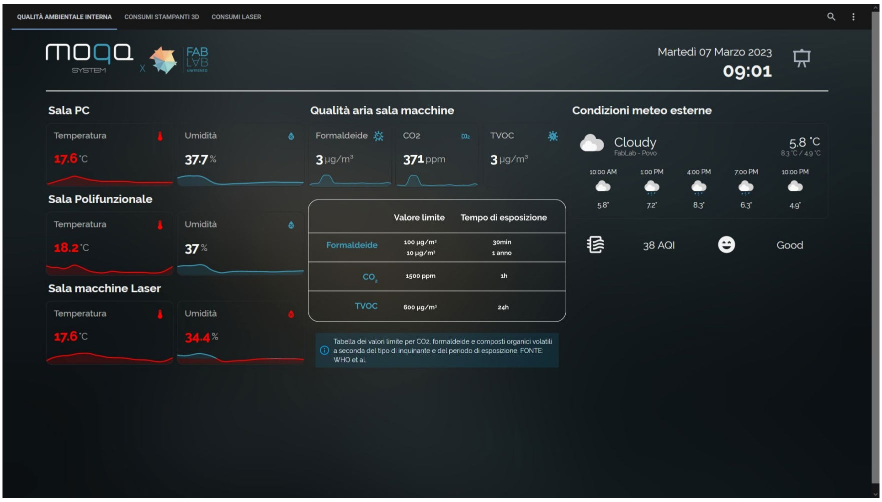
Fig. 5.7 MOQA dashboard – version 1. a) IEQ dashboard; b) Energy dashboard

	Valore limite	Tempo di esposizione
Formaldeide	100 µg/m³ 10 µg/m³	30min 1 anno
CO_2	1500 ppm	1h
TVOC	600 µg/m³	24h

Tabella dei valori limite per CO2, formaldeide e composti organici volatili a seconda del tipo di inquinante e del periodo di esposizione. FONTE: WHO et al.

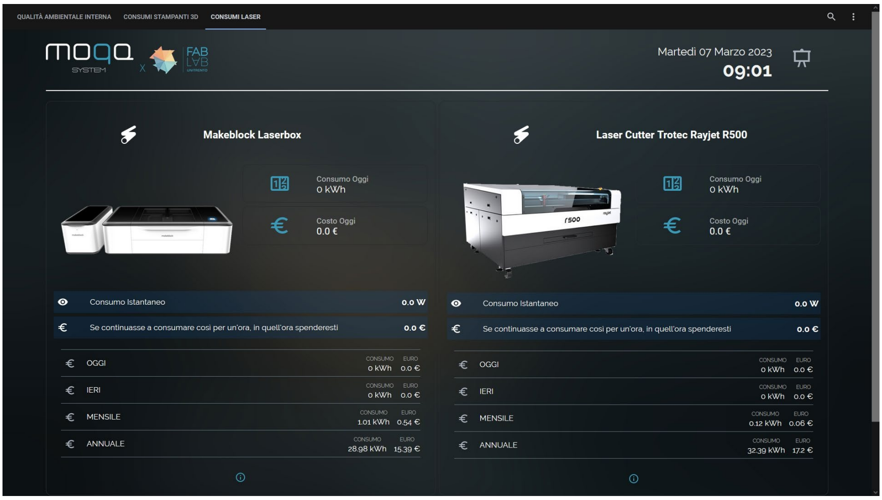
Participants were then introduced to the new version of the dashboard (shown in Fig. 5.8) and asked to perform tasks on a prototype visualized through Figma (MOQA (figma.com)).

Fig. 5.8 MOQA dashboard – version 2. a) IEQ dashboard; b) Energy dashboard



	Valore limite	Tempo di esposizione
Formaldeide	100 µg/m³ 10 µg/m³	30min 1 anno
CO_2	1500 ppm	1h
TVOC	600 µg/m³	24h

Tabella dei valori limite per CO2, formaldeide e composti organici volatili a seconda del tipo di inquinante e del periodo di esposizione. FONTE: WHO et al.



Martedì 07 Marzo 2023
09:01

Makeblock Laserbox

Consumo Oggi 0 kWh
Costo Oggi 0.0 €
Consumo Istantaneo 0.0 W
Se continuasse a consumare così per un'ora, in quell'ora spenderesti 0.0 €

	CONSUMO	EURO
OGGI	0 kWh	0.0 €
IERI	0 kWh	0.0 €
MENSILE	1.01 kWh	0.54 €
ANNUALE	28.98 kWh	15.39 €

Laser Cutter Trotec Rayjet R500

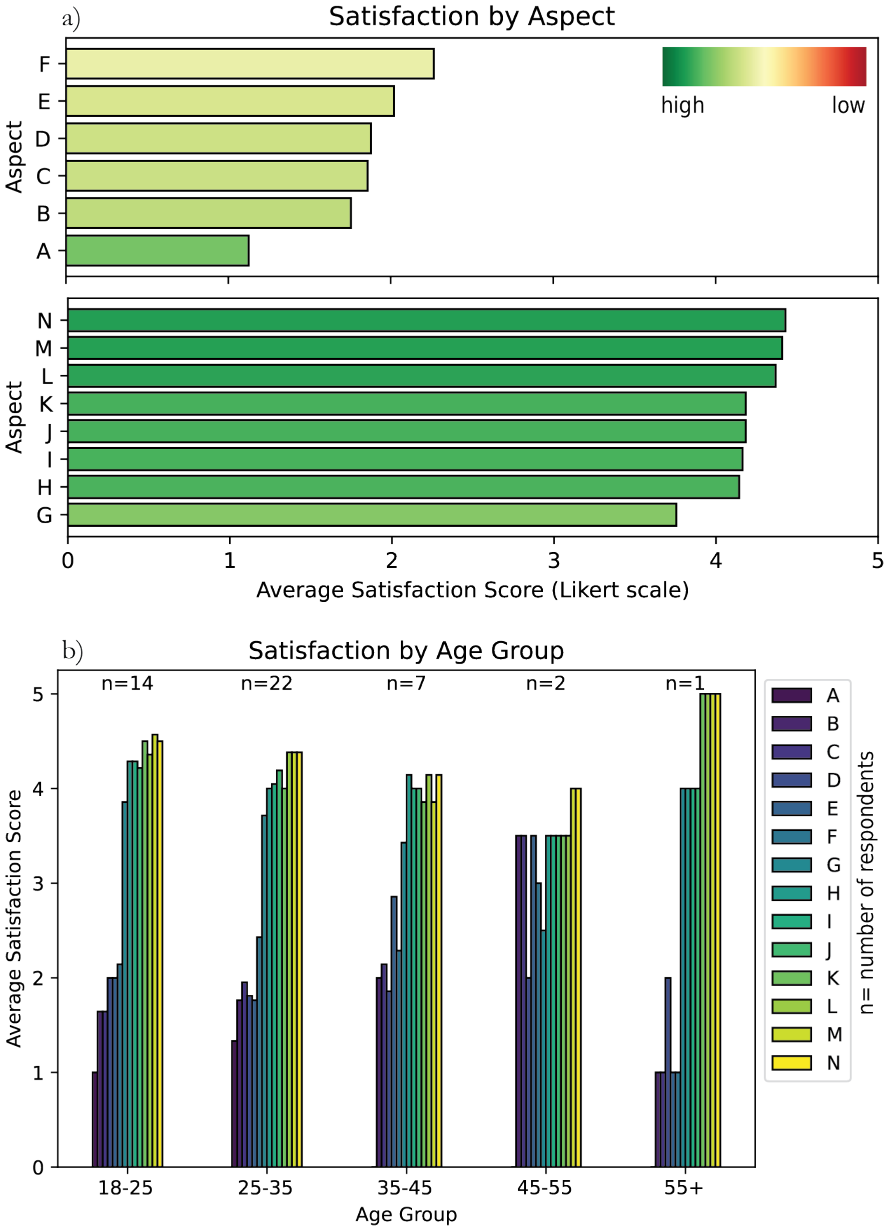
Consumo Oggi 0 kWh
Costo Oggi 0.0 €
Consumo Istantaneo 0.0 W
Se continuasse a consumare così per un'ora, in quell'ora spenderesti 0.0 €

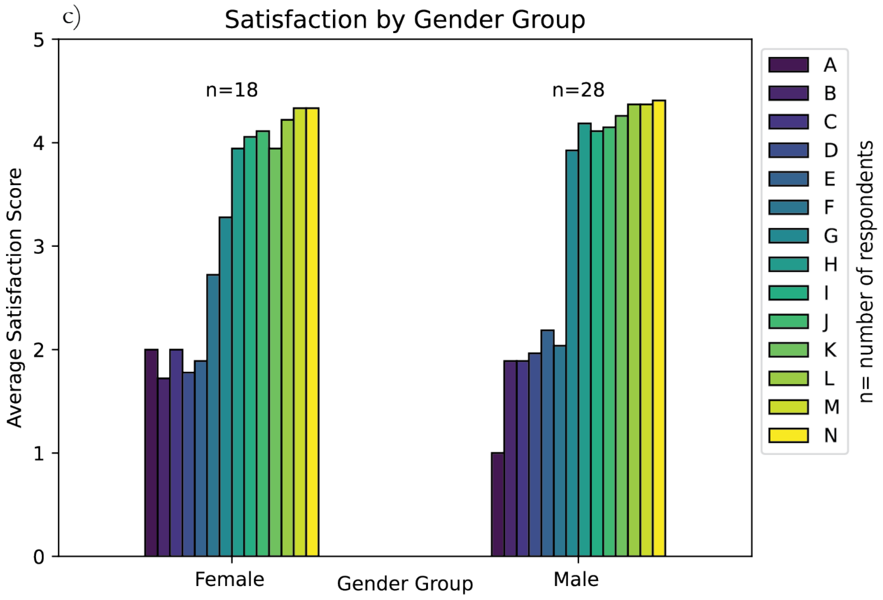
	CONSUMO	EURO
OGGI	0 kWh	0.0 €
IERI	0 kWh	0.0 €
MENSILE	0.12 kWh	0.06 €
ANNUALE	32.39 kWh	17.2 €

This approach allowed participants to interact with both versions, providing a basis for comparing the two and offering suggestions for improvements and additional features. Surveys complemented the interviews, aiming to gather both qualitative and quantitative feedback on the interface. The survey questions employed a Likert scale, ranging from 1 to 5, with options from "strongly agree" to "strongly disagree". This scale provided a structured way to measure users' attitudes and perceptions. Additionally, open-ended questions were included to capture more detailed and nuanced responses.

A total of 10 interviews and 50 surveys were conducted. The survey questions were designed to address the previously mentioned aspects: information efficiency (Aspect A), usability (aspects B, C, G, I, J), quality of interaction (aspects D, E, F), functionality (Aspect K), and acceptability (Aspects H, L, M, N). Aesthetic considerations were primarily explored through the interviews, which allowed for a more direct experience and in-depth questioning, although some insights were also gleaned from the open-ended questions in the survey. Fig. 5.9 presents the survey results, focusing particularly on user satisfaction with Version 2 of the dashboard. The participant demographics were fairly evenly split between males and females, with a significantly higher proportion of individuals under 35 compared to those over 35. However, the findings did not show substantial differences between these demographic categories.

Fig. 5.9 MOQA dashboard satisfaction levels





Aspect Description

A: I found inconsistencies between the various features of the platform
B: I found the platform unnecessarily complex
C: I found the platform cumbersome to use
D: I needed to learn many processes before I was able to use the platform to the fullest
E: I got bored performing the activity
F: I think I would need the support of a person already able to use the platform
G: I felt comfortable using the platform
H: I think most people can learn to use the platform easily
I: I think the activity is intuitive
J: I found the platform easy to use
K: I found the various features of the platform well integrated
L: I think I would like to use this platform frequently
M: I would recommend the platform to others
N: I would use the platform to monitor the environments in which I live

Based on the feedback obtained from the interviews and surveys, Version 1 of the MOQA dashboard was critiqued for its lack of visual appeal, primarily due to a homogenous color scheme that resulted in a monotonous display. The graphs were found to be difficult to understand and not user-friendly, lacking intuitive design elements that would make data interpretation straightforward for users. Issues with scaling and responsiveness were also highlighted, indicating that the dashboard was not optimally viewable across different devices or screen sizes. Furthermore, the layout, especially how different rooms were segmented, was noted as an area needing improvement to enhance user navigation and comprehension. While users could perform basic functions like retrieving historical data from the graphs without much difficulty, the dashboard was considered more effective for providing a broad overview rather than a detailed analysis of the data.

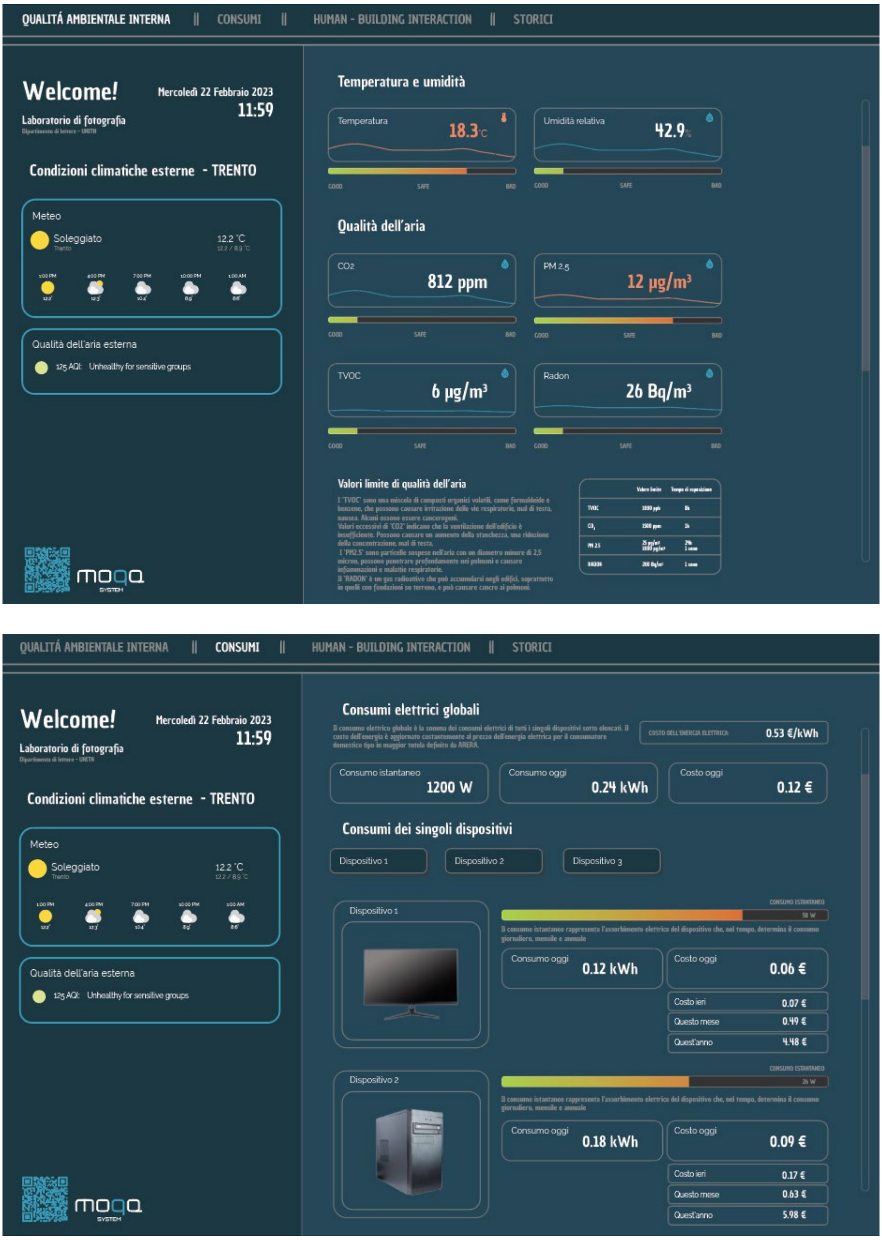
Subsequent advances in interface design led to version 2. The main enhancements introduced were:

- Modular Code Development: The code was organized into separate YAML files for each column or row of the dashboard. Key additions included:
    - A common header across all views featuring logos, date/time, and a presentation mode button.
    - View 1 (IEQ dashboard) displays temperature and humidity in the leftmost column for three laboratory rooms, air quality information in the central column for the laser machine room, and external weather and outdoor air quality in the rightmost column.
    - Views 2 and 3 (Energy dashboards), dedicated to 3D printers and laser cutting machines, respectively, employ a double-column design to show detailed machine status, including images, daily and instantaneous consumption, and a summary table.
- New Tabs:
    - External weather tab utilizing OpenWeatherMap API.
    - Outdoor air quality tab using IQ Air API.
    - A tab for detecting the average electricity price, calculated via a Python script querying the ARERA website.
    - Presentation mode for automatic switching between views on a fixed monitor.
- Graphical Improvements:
    - A logical rearrangement of tabs based on location/function.
    - Dynamic graph coloring based on threshold values for better visual cues.
    - Enhanced responsiveness with CSS for adaptable tab and font sizes, making the dashboard suitable for various resolutions.

These enhancements led to a more modern and user-friendly design that not only addressed the aesthetic shortcomings but also improved the overall functionality and user experience. The updated dashboard, with better visual distinction, intuitive graphs, and responsive design, facilitated a more engaging and insightful interaction with the data, aligning with the users' needs for both a general understanding and a detailed analysis. The interface's increased responsiveness was well-received by respondents, and the integration of external weather and air quality data was considered a valuable addition, although some users suggested that these elements might be better placed in a separate tab to streamline the user experience. The features displaying instantaneous consumption and hourly costs were praised for their utility, yet users advised that it should be made clear that the costs were estimates. They suggested providing an option for users to input their actual utility rates for more personalized and accurate cost calculations. To further boost user engagement, suggestions were made to introduce interactive elements like lighting control and monitoring material consumption for 3D printers. These recommendations pointed towards a more participative user interface that would enable direct interaction with the environment and devices within it. While the dynamic color scheme of the graphs in the revised design was acknowledged as an improvement, aiding in task execution, there was feedback indicating that the colors used were too similar and dark, which could lead to confusion when distinguishing between different data points. Additionally, issues with unintelligible graphs, scaling, and responsiveness persisted, indicating that these aspects still required attention.

Despite the advancements made with Version 2 of the MOQA dashboard, feedback highlighted that issues with clarity, intuitiveness, and responsiveness persisted, necessitating further refinement. In response to this feedback, a final version of the dashboard was conceptualized (Fig. 5.10), which incorporated the key insights gained during the user feedback campaign. This final iteration aimed to address the remaining deficiencies by reorganizing the dashboard layout, enhancing the visual contrast of graphs, and improving the system's responsiveness across different devices. The organization of the dashboard and the associated code are detailed in Appendix D, ensuring transparency and enabling potential future updates to align with user requirements and technological advancements.

Fig. 5.10 MOQA dashboard – version 3. a) IEQ dashboard; b) Energy dashboard



Welcome!
Mercoledì 22 Febbraio 2023
11:59
Laboratorio di fotografia
Dipartimento di lettere - UNITN

Condizioni climatiche esterne - TRENTO

Meteo
Soleggiato
Trento
12.2 °C
12.2 / 8.9 °C

Qualità dell'aria esterna
125 AQI: Unhealthy for sensitive groups

Temperatura e umidità
Temperatura 18.3 °C
Umidità relativa 42.9 %

Qualità dell'aria
CO2 812 ppm
PM 2.5 12 µg/m³
TVOC 6 µg/m³
Radon 26 Bq/m³

Valori limite di qualità dell'aria

I 'TVOC' sono una miscela di composti organici volatili, come formaldeide e benzene, che possono causare irritazione delle vie respiratorie, mal di testa, nausea. Alcuni ossono essere cancerogeni.
Valori eccessivi di 'CO2' indicano che la ventilazione dell'edificio è insufficiente. Possono causare un aumento della stanchezza, una riduzione della concentrazione, mal di testa.
I 'PM2.5' sono particelle sospese nell'aria con un diametro minore di 2,5 micron, possono penetrare profondamente nei polmoni e causare infiammazioni e malattie respiratorie.
Il 'RADON' è un gas radioattivo che può accumularsi negli edifici, soprattutto in quelli con fondazioni su terreno, e può causare cancro ai polmoni.

	Valore limite	Tempo di esposizione
TVOC	1000 ppb	8h
CO_2	1500 ppm	8h
PM 2.5	25 µg/m³ 1000 µg/m³	24h 1 anno
RADON	200 Bq/m³	1 anno

Consumi elettrici globali

Il consumo elettrico globale è la somma dei consumi elettrici di tutti i singoli dispositivi sotto elencati. Il costo dell'energia è aggiornato costantemente al prezzo dell'energia elettrica per il consumatore domestico tipo in maggior tutela definito da ARERA.

COSTO DELL'ENERGIA ELETTRICA: 0.53 €/kWh
Consumo istantaneo 1200 W
Consumo oggi 0.24 kWh
Costo oggi 0.12 €

Consumi dei singoli dispositivi
Dispositivo 1
Dispositivo 2
Dispositivo 3

Dispositivo 1
CONSUMO ISTANTANEO 58 W
Il consumo istantaneo rappresenta l'assorbimento elettrico del dispositivo che, nel tempo, determina il consumo giornaliero, mensile e annuale
Consumo oggi 0.12 kWh
Costo oggi 0.06 €
Costo ieri 0.07 €
Questo mese 0.49 €
Quest'anno 4.48 €

Dispositivo 2
CONSUMO ISTANTANEO 26 W
Il consumo istantaneo rappresenta l'assorbimento elettrico del dispositivo che, nel tempo, determina il consumo giornaliero, mensile e annuale
Consumo oggi 0.18 kWh
Costo oggi 0.09 €
Costo ieri 0.17 €
Questo mese 0.63 €
Quest'anno 5.98 €

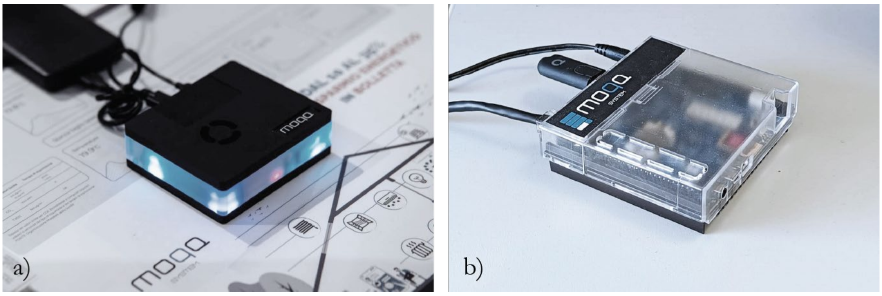
5.2.6 Housing design

Considerable attention has been devoted to the aesthetics of the housing that encloses the electronic components, aiming to create a product that can be seamlessly integrated within the indoor spaces to be monitored. These spaces are inhabited by individuals who may occasionally express reservations regarding the intrusion of such technology into their domestic environment.

While system performance was the primary design consideration, it was recognized that assembling various devices and components in a single case would involve trade-offs. The first compromise related to the commercial availability of the main hardware. During a historical period in which geopolitical factors have caused the cost of electronic products to significantly increase and their availability to reach historic lows, the project necessitated the creation of two prototypes. The first accommodated a Raspberry Pi4, while the second hosted an Odroid N2+. This decision was driven by the limited availability of a unique, easily purchasable single-board computer during this historical period.

For the first prototype (Fig. 5.11a), developed in collaboration with the Fablab of the University of Trento, a robust acrylic plastic casing with a modern design was chosen. The distinctive feature is the housing's closure mechanism, which can be easily assembled in a few steps, thanks to small magnets located at the top, center, and bottom of the casing. The case also provides direct access to various ports, including the GPIO, which is only covered by a simple lid. An integrated fan and two included heat sinks ensure consistent cooling for the Raspberry Pi 4B. The case also features 4 RGB LEDs on each corner that can be programmed for operation and color using Hyperion, an open-source ambient light implementation compatible with many platforms. For promotional purposes, a blue LED was chosen to align with the MOQA logo, which is engraved in its black and white version on the case. However, this lighting is disabled during monitoring campaigns, as it is often not appreciated by those who need to place the system in their homes and may be disturbed by additional lights. The hard disk, with a minimum size of 32GB, is located externally to the case and connected via a USB port. The next evolution of the prototype, currently under construction, will involve an M.2 format Solid State Drive (SSD) installed directly on the motherboard.

Fig. 5.11 MOQA prototypes



The second prototype (Fig. 5.11b), which is simpler and more cost-effective, is made from strong and durable semi-transparent polycarbonate plastic. The magnetic assembly has been replaced with a more traditional snap-fit assembly method, and the LED customization has been removed, with standby LEDs minimized. The MOQA logo is now applied using a vinyl sticker rather than being engraved on the case. The external hard disk has been replaced with a compact 32GB eMMC storage, which is directly installed on the motherboard of the Odroid N2+ and placed internally within the case.

A standard Ethernet cable transmits data to the mainboard processor via serial communication, providing an internet connection. In the first prototype, the Raspberry Pi4 includes an internal Wi-Fi module, allowing also for wireless connectivity. While this solution proved to be less stable, it remained a viable option for short-duration monitoring campaigns and situations where an Ethernet connection is not feasible. The USB dongles and gateways required for communication across multiple protocols are currently externally connected to the case via USB for both prototypes. Finally, the power cable equipped with a transformer completes the setup.

The fact that MOQA operates as a smart hub and does not contain sensors in its case – unlike many of the examples presented in section 5.1 – has avoided interference between the waste heat from electronic components, such as the power circuit or heat sinks, and temperature-sensitive devices or sensors. Similarly, it was not necessary to assess the impact of the prototype's materials, and their potential release of chemical compounds, on the indoor air quality sensors.

5.3 Concluding remarks

MOQA, developed as part of this doctoral research, represents an innovative approach to home monitoring and automation. In contrast to conventional systems, MOQA distinguishes itself with its open-source framework and versatile data integration capabilities, enabling the seamless assimilation of various data sources, both environmental and non-environmental. This system not only demonstrates the potential of integrating diverse data but also underscores the importance of converting such data into understandable insights through a user-centric dashboard. MOQA's architecture accommodates a wide range of sensors and hardware, adhering to principles of cost-effectiveness and operational efficiency. Its adaptability to different contexts and resilience also to the technology market fluctuations highlight its practicality for widespread adoption. The iterative design process of MOQA's user interface, informed by user feedback from extensive monitoring campaigns, emphasizes the significance of a dashboard that is not only visually appealing but also intuitive and responsive. The implementation of modular code, application of responsive design principles, and strategic organization of data visualization elements reflect ongoing improvements aimed at enhancing user interaction. In summary, MOQA represents a thoughtful fusion of cost-effectiveness, scientific accuracy, and user engagement, aiming to provide a sustainable and inclusive tool for building management. It stands as a significant contribution to the field of smart home automation, offering a blueprint for future systems to deliver high-performance building applications that prioritize both environmental sustainability and user experience.

6 Cross-Sectional Study of MOQA Implementation in Different Indoor Environments

"The value of an idea lies in the using of it."

THOMAS A. EDISON

6.1 Background and aim

The assessment of indoor comfort and energy consumption requires an integrated approach that merges quantitative and qualitative methodologies. Comfort, often associated with personal well-being and satisfaction [43], encompasses subjective qualities that are not readily quantifiable. Similarly, energy use, while measurable, is influenced by human behaviors and preferences that cannot be fully understood through metrics alone. At the same time, purely verbal accounts fail to quantify the physical conditions that generate comfort or discomfort and impact on energy efficiency. In addressing this dichotomy, a mixed-method approach [352] is vital, leveraging the strengths of both quantitative precision and qualitative depth to capture the full spectrum of the concept. In building science, the investigation of occupant comfort and energy use has traditionally been conducted within controlled environments or through in-situ surveys [227], utilizing input via structured questionnaires designed to convert subjective experiences into objective data. This convention arises from the notion that layperson perceptions may not accurately reflect their behaviors or the subtleties that affect comfort and energy consumption [353]. Yet, such quantitatively inclined methods, grounded in correlations and statistical analysis, may not fully encapsulate the subjective human experience.

The purpose of this chapter is to present the deployment of the MOQA system across different settings, thereby illustrating the application of both qualitative and quantitative approaches. MOQA has been installed in various contexts, including five public housing apartments in Rovigo, Italy, under the "Contratti di Quartiere II" project, and various university premises through the ongoing "M&asure" project. Subsequent sections will delve into:

- The qualitative aspect through interviews with public housing residents, offering insights into the lived experiences and personal receptions of the MOQA system (Section 6.2).
- Quantitative evaluations from surveys conducted in the university's Fablab, analyzing students' interactions with the system (Section 6.3).
- A detailed examination of a customized thermal feedback collection system and its relationship with environmental data gathered in the public housing initiative (Section 6.4).
- A discussion on an alternative feedback collection approach proposed by Tartarini et al. [344], and its application to the M&asure project (Section 6.5).

The chapter will conclude with a synthesis of findings from these case studies, drawing a comprehensive picture that juxtaposes and compares the diverse experiences, reflecting on the nuanced ways in which occupants engage with their environment and the MOQA system.

6.2 MOQA in daily life: family experiences in public housing

The study presented in this Section, part of the "Contratti di Quartiere II" project, embarks on an investigative journey into the lived experiences of 5 families residing in public housing in Rovigo (IT), where the MOQA system has been integrated into their daily lives, serving not only as a tool for environmental monitoring and energy management but also as a lens through which the subtleties of domestic comfort are revealed. This research aims to delve into the perceptions, interactions, and adaptations of families as they navigate the intersection of technology, space, personal comfort, and energy use.

Methodology

The research questions at the heart of the study necessitated the use of exploratory and qualitative data gathering methods, given the subjectivity behind the topic of comfort and energy use in residential buildings: interviews thus represent the optimal medium to document the diverse perspectives individuals hold about a common situation or subject.

As Fontana and Frey [354] assert, however, although interviews are a powerful way to comprehend our human experiences, the format of these interviews can significantly influence the depth and quality of data collected. Structured interviews, in fact, while offering consistency through a uniform set of questions and predefined response options, were deemed unsuitable for this research due to the indeterminate nature of mental factors influencing housing experience at the data collection stage. Conversely, unstructured interviews, which lack predetermined questions and allow respondents to guide the conversation, were considered too open for the specific focus required to gather data on comfort and energy use [355]. The choice of semi-structured interviews as the primary data collection method was then deliberate, given the exploratory nature of this research. This approach allowed for the flexibility to probe deeper into the responses of participants, offering them the freedom to express their perspectives in a more open-ended dialogue, while still providing a consistent structure to compare across interviews [356]. According to Kahneman and Klein [357], people have developed an intuitive system, honed by continuous interaction with built environments, enabling them to subconsciously interpret cues and make inferences about environmental quality. The design of the interview leveraged this intuitive understanding, inviting participants to describe, in their own words, the characteristics of a dwelling that epitomized comfort and energy efficiency for them.

The research was structured in two distinct phases. The first phase involved a set of seven questions (Appendix E), designed to capture the families' experiences with the installation of the MOQA system and after living with the system for one year without access to the data it collected. This initial set aimed to explore the expectations, apprehensions, and perceived changes brought about by MOQA's presence in their homes. A second set of seven questions (Appendix E) was prepared for the subsequent phase, intending to investigate the changes in the families' perceptions and interactions with the MOQA system after they were provided with real-time access to the environmental and energy data monitored. This phase was designed to offer insights into how direct engagement with the data might alter the families' understanding and usage of the system, potentially influencing their energy consumption behaviors and comfort levels. The overarching goal was to provide a comprehensive overview of the perspectives of five distinct families on the MOQA system, covering a spectrum of experiences from anticipation to adaptation and potential behavior modification. Regrettably, due to unforeseen delays in the "Contratti di Quartiere II" project, compounded by its dependence on ministerial funding and the inherent complexities of the public housing context, the second phase of the research could not be completed as planned. Consequently, the results from this phase remain pending, and the anticipated comparative analysis across the two phases is currently unavailable. However, the methodology established for this study lays a robust foundation for future research, ensuring that when circumstances permit, the second phase can be executed seamlessly to fulfill the study's objectives.

The study engaged with five households across three different buildings in the heart of Rovigo (IT), whose proximity provided a consistent environmental context for the deployment of the MOQA system. A snapshot of each apartment and the household composition is captured in Tab. 6.1, where each household is assigned a unique identifier for ease of reference and analysis.

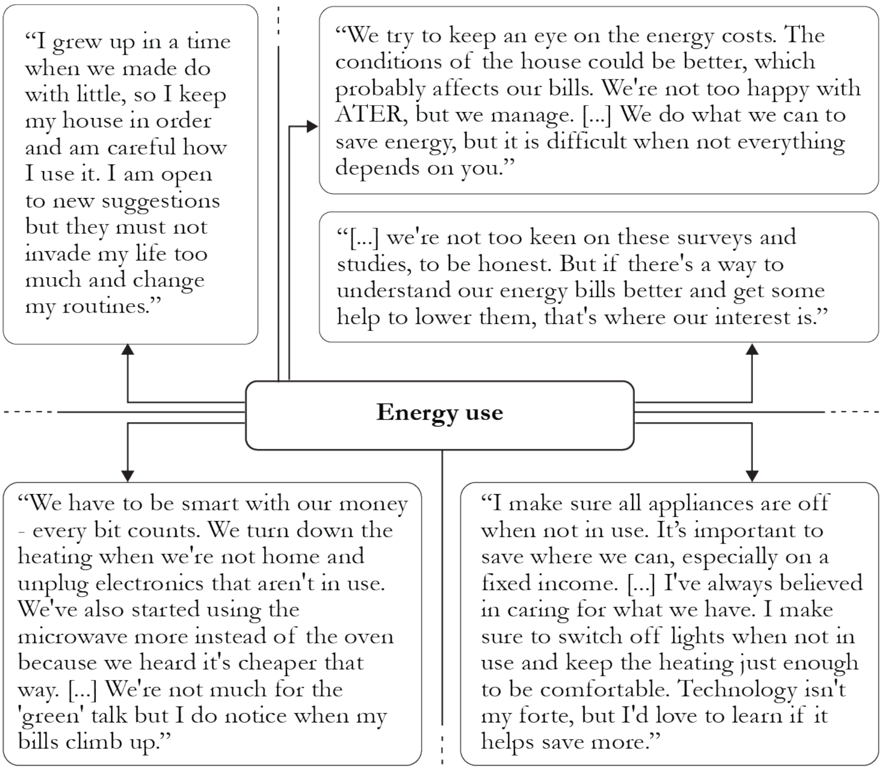
Tab. 6.1 Description of the flats and involved households.

Flat n.	*Building n.*	*Building Heating Energy Use Intensity [kWh/m^2.yr]*	*Flat orientation*	*Flat floor area [m^2]*	*Household composition*
1	1	132.69	South+West	70	1 old lady
2	2	156.93	South+West +East	76	Middle-aged couple
3	2	156.93	East+West	80	Middle-aged couple + 1 son
4	1	132.62	North	54	Mother and daughter
5	3	178.69	South+North	87	Mother and son

The participant families were selected through a collaborative process led by ATER Rovigo, the owner of the residential buildings. The buildings were selected because earmarked for energy efficiency enhancements as part of the broader "Contratti di Quartiere II" project. The selection criteria of the apartment and the households, instead, hinged on the people willingness to participate, occupancy status, ease of access for communication, and a natural inclination towards engaging with the project. Upon selection, families were introduced to the MOQA system through a community presentation. This session, orchestrated by both the research team and ATER Rovigo in November 2021, outlined the data collection procedures and the overarching goals of the project, securing the definitive participation of the residents. In the weeks following the initial briefing, the MOQA system was installed. As mentioned before, the first year post-installation did not include data visibility for the residents, while the second year should have provided them with a real-time data dashboard. At the conclusion of the initial year (December 2022), interviews were conducted using the first set of seven questions (Appendix E).

Each interview spanned approximately 20 to 25 minutes. Considering the sensitivity of some participants, interviews were not recorded; instead, extensive written notes were taken. Although the subject matter was not expected to stir controversy, confidentiality was assured to all respondents. Additionally, since interviews were conducted in person, participants were encouraged to engage actively, even contributing to the note-taking process to ensure accuracy and a shared understanding. The written notes were subsequently organized into mind maps, following the methodology proposed by Molina [49], exemplified by a sample in Fig. 6.1. The data was then analyzed using the Thematic Analysis method as elucidated by Braun and Clarke [358], [359].

Fig. 6.1 A small piece of the mind map that resulted from different interviews about energy use.



"I grew up in a time when we made do with little, so I keep my house in order and am careful how I use it. I am open to new suggestions but they must not invade my life too much and change my routines."

"We try to keep an eye on the energy costs. The conditions of the house could be better, which probably affects our bills. We're not too happy with ATER, but we manage. [...] We do what we can to save energy, but it is difficult when not everything depends on you."

"[...] we're not too keen on these surveys and studies, to be honest. But if there's a way to understand our energy bills better and get some help to lower them, that's where our interest is."

"We have to be smart with our money - every bit counts. We turn down the heating when we're not home and unplug electronics that aren't in use. We've also started using the microwave more instead of the oven because we heard it's cheaper that way. [...] We're not much for the 'green' talk but I do notice when my bills climb up."

"I make sure all appliances are off when not in use. It's important to save where we can, especially on a fixed income. [...] I've always believed in caring for what we have. I make sure to switch off lights when not in use and keep the heating just enough to be comfortable. Technology isn't my forte, but I'd love to learn if it helps save more."

The thematic analysis process entailed several steps:

- Familiarization with Data: The interviewer's direct analysis of the data enabled a nuanced comprehension, which was augmented using mind maps.
- Initial Code Generation: Every concept or phrase, serving as nodes in the mind maps, received specific codes, as recommended by Braun and Clarke [358].
- Theme Searching: Codes were then elevated to themes, each capturing significant patterns related to the research questions.
- Theme Reviewing: This critical review ensured the themes were supported by data and were distinct in their representation of the concepts.
- Theme Defining and Naming: Detailed analysis for each theme was conducted to capture its essence, crucial for the interpretative framework of the study.

- Reporting: Unfortunately, this phase was not fully completed due to the absence of the second set of interviews.

In summary, this interview methodology yielded a comprehensive list of factors that potentially influence comfort and energy use. Those frequently mentioned by participants are presumed to resonate with a larger segment of the target population, thus warranting further study. Even factors mentioned infrequently are considered for their potential relevance, with the understanding that subsequent research may confirm or refute their impact. The forthcoming section represents a work still in progress, pending the completion of the second round of interviews. The responses have been clustered thematically and examined through the constructed mind maps. A more comprehensive presentation of these mind maps, alongside a detailed discussion of the findings, will be developed and published upon the completion of the research work. To maintain readability and conciseness, the chapter presents only select quotes in the results section, chosen for their representation of the core arguments.

Results and discussion

The interview responses were analyzed using the described methodology, **identifying seven main themes**:

- **Energy Use**: A topic that explores how families use energy and their daily habits concerning energy consumption.
- **Comfort**: Central to the analysis of household decisions, it involves how families balance comfort with energy use.
- **Environmental Awareness**: Examines how environmental awareness affects energy decisions and the adoption of monitoring technologies.
- **Home Practices**: This theme investigates the daily routines and habits of families in relation to energy consumption and comfort.
- **Technology Adoption**: Crucial for understanding how families adapt to the use of new technologies for energy monitoring and beyond.
- **Monitoring**: Relevant in examining the acceptance and impact of monitoring the energy behavior and decisions of families.

- **Benefits and Disadvantages**: Analyzes how families perceive the benefits of the monitoring system, both in terms of energy savings and improving the quality of life.

In discussing "energy use", the interviewees tended to equate energy usage with energy costs. When asked to talk about energy consumption or energy savings, their responses invariably focused on utility bills or costs to be paid.

"[…] We try to keep an eye on the energy costs."

The interview period coincided with a steep increase in energy costs (winter 2021-2022), which undoubtedly influenced the perception of the problem and led to a hectic search for solutions to optimize energy use, including on the web.

"[…] I was looking for advice on household energy usage and how to save money. Last week, I had to search for a new electricity plan for the first time in three years."

"We've also started using the microwave more instead of the oven because we heard it's cheaper that way."

The fact that all interviewees were renting accommodations owned by ATER often led to discussions about their relationship with the landlords/managers, with a general tendency to split the responsibilities for energy use equally between both parties.

"We're not too happy with ATER, but we manage. [...] We do what we can to save energy, but it is difficult when not everything depends on you."

This aspect also influenced indoor comfort:

"The conditions of the house could be better, which probably affects our bills."

The environmental conditions, but especially the construction characteristics and maintenance levels of the buildings, varied significantly. In one specific case, the dwelling was in poor sanitary conditions, and the entire interview could be summarized as a dispute between tenants and managers. More generally, there were very few references to comfort, and these were limited to some personal considerations.

"There's no better feeling than making use of the sunlight... I absolutely adore it."

Most responses on the topic pertained more to discomfort, or rather to the trade-offs between energy consumption and set-point temperatures, than to comfort itself.

"[…] We keep the sleeping areas cool, while the living room temperature is higher."

"I am aware that raising the thermostat leads to higher bills, which sometimes leads me to choose to endure the cold."

Although it wasn't a primary focus in the interviews, the topic of environmental awareness and responsibility came up frequently, likely influenced by the heightened public interest in this topic during the period when the interviews were conducted.

"[…] We're not much for the 'green' talk but I do notice when my bills climb up."

Environmental concerns do not emerge as a driving factor for energy-saving strategies, and the environmental impact of personal actions is perceived as less significant compared to other scenarios. Improving them is not seen as an effective solution.

"The goal is to shut down the methane gas supply and switch to electricity without compromising comfort and, ideally, without excessively increasing energy costs. [...] The environmental aspect also plays a role, but I'm also afraid of gas."

"[...] certainly, our behavior has an impact on the environment, but industries are worse."

Another aspect of sustainability is revealed, primarily from those who have lived in the same house for a long time. Three out of five families emphasized how principles of behavior and the education they received in the past influence their current approach to managing their household.

"I grew up in a time when we made do with little, so I keep my house in order and am careful how I use it."

"I've always believed in caring for what we have."

Reducing energy consumption is accomplished through fairly standard practices.

"I make sure all appliances are off when not in use."

"Using less [energy]? Simple: Sweaters, cardigans, thicker blankets..."

"I make sure to switch off lights when not in use and keep the heating just enough to be comfortable."

"We turn down the heating when we're not home and unplug electronics that aren't in use."

However, in some instances, changing "long-established" habits can be challenging, as these practices may be energy-intensive but also carry symbolic significance and intrinsic value for individuals.

"Since I've been living alone, I don't share expenses anymore.... But it's still important to me...[...] I couldn't live without a space heater when I take a shower."

Resistance to change is a common thread in many of the responses related to technology and monitoring, despite the expressed willingness to participate in the research after the purpose, methods, and tools used were adequately explained and illustrated.

"Technology isn't my forte, but I'd love to learn if it helps save more."

The interest in participating is, once again, connected to the benefits in terms of energy cost reduction, with all participants showing concern from the early stages about the impact of installing the monitoring system on their electricity bills.

"[…] But if there's a way to understand our energy bills better and get some help to lower them, that's where our interest is."

"But how much do all this technology and sensors consume?"

Every household had their primary environmental thermostat replaced with a smart thermostat capable of providing additional details on the user-HVAC system-building relationship and directly integrated into MOQA. The acceptance of the thermostat (model: Netatmo) was gradual.

"My thermostat is 20 years old and has always worked perfectly. Are you sure this new one will work just as well?"

"I was hesitant about the new thermostat, but it's actually better than the old one. It's more intuitive, and the temperature it measures is the same as this mercury thermometer, which is always accurate!"

Once reassured about the energy consumption of the monitoring system and its sensors, multiple respondents recognized the primary advantage of the system as gaining an accurate understanding of the energy consumption of various home appliances. Environmental variables (such as thermal, light, acoustic, and air quality) were not highlighted as primary aspects of interest for monitoring. Additionally, the topic of privacy did not notably concern the five surveyed households.

"I've always wondered how much the microwave consumes. It's clear it's old and often causes power outages."

"Is it true what they say about saving energy by unplugging electronic devices on standby? How much would I save?"

Clearly, solutions are needed to elucidate the meaning of "energy consumption" to end users and to improve the clarity of information provided in utility bills.

"I'm still not clear on the difference between kW and kWh; if you speak to me about euros, I understand."

Regarding the advantages and disadvantages of the system, the responses were quite vague in the initial interviews, and the lack of real-time data visualization obviously affected the inhabitants' ability to receive suggestions.

"I am open to new suggestions, but they must not invade my life too much and change my routines."

The main questions that the system can answer through the collected data were asked directly to the person who installed the system. This discussion not only focused on the monitoring duration but also questioned the true necessity of accumulating such extensive data to address what are seen as relatively simple questions.

"How long will the monitoring last? Do we need all these months?"

"I trust what you tell me more than the numbers!"

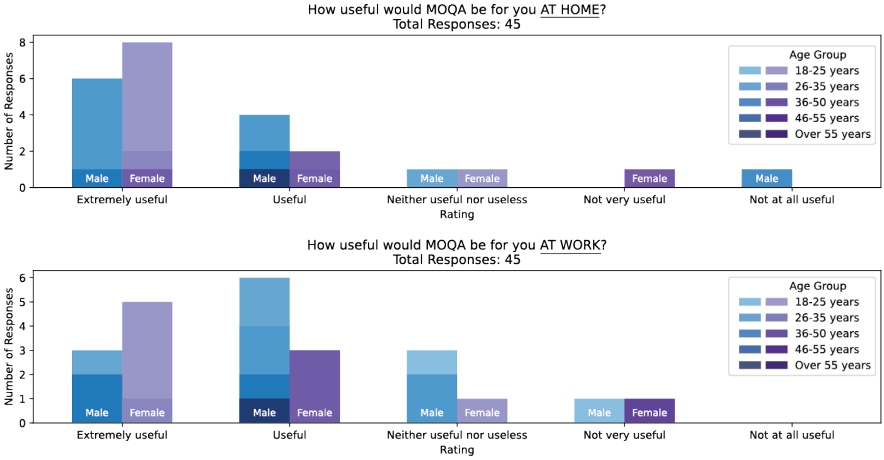
It is evident that the outcomes here presented are preliminary and rather limited in scope. First and foremost, the number of interviewees is quite small, which inherently limits the breadth of data. The selection of participants was also influenced by the practical need to identify apartments suitable for the upcoming renovation phase in the "Contratti di Quartiere II" project. This means that all the respondents are from a very specific demographic – renters in public housing – which may affect the applicability of the findings to a broader population. However, within the scope of the MOQA system installation, the interviews can be considered representative as they encompass all participants who experienced the system in their homes. It's important to note that installing a monitoring system is both time-consuming and costly, which justifies the decision to interview only those who have interacted directly with MOQA. Another limitation is the potential for misrepresentation of respondents' thoughts. While transparency with note-taking was maintained throughout the interview process, the absence of recorded interviews means that there is no definitive confirmation that the transcribed thoughts perfectly mirror those of the interviewees. To mitigate this, it is proposed that a future step in the research should involve presenting the created mind maps back to the participants, allowing them to suggest any modifications, thus ensuring the accuracy and authenticity of the reported data. This first set of findings serve as a basis for further exploration and deeper analysis in later stages of the research. They offer valuable insights, laying the groundwork for a more comprehensive understanding as the study proceeds, especially as it delves into subsequent tranches of interviews.

6.3 MOQA usage and perceptions: survey insights

The utility of the MOQA system, its level of use, and the identification of functions to correct or enhance were investigated not only through the case study described in section 6.2 but also via the questionnaire discussed in chapter 5.2.5 concerning the dashboard design. This questionnaire, administered during a six-month monitoring campaign at the Fablab UniTrento (see Section 5.2.5 for details on methodology), in addition to questions about information efficiency, usability, quality of interaction, functionality, and acceptability of the platform, asked the occupants to report on the general perceived utility of the system. Out of 50 participants (17 females, 28 males), 45 contributed to the results presented in Fig. 6.2, with 5 opting not to disclose their gender, thus not reflected in the graphical data. The figure illustrates an interesting set of data on the perceived utility of the

MOQA system, differentiated by gender and age group, and categorized by potential use at home and at work according to a Likert scale.

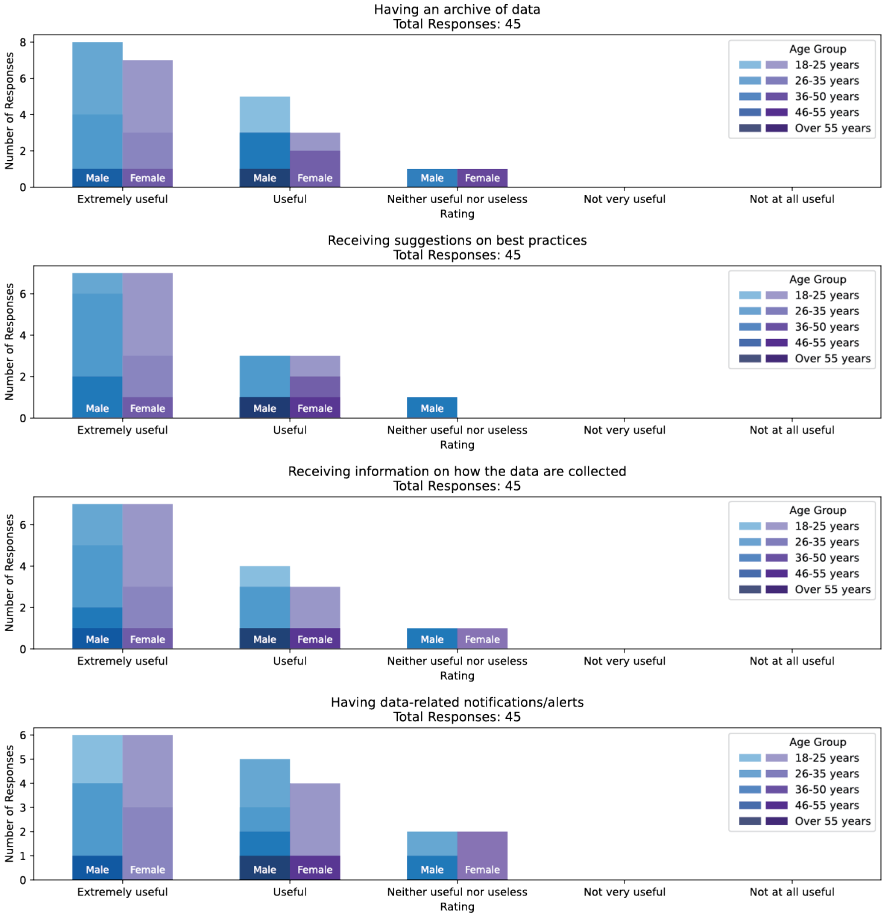
Fig. 6.2 Overall perceived utility of the MOQA system.



From the first graph, it is evident that MOQA is considered 'Extremely useful' at home by a majority of female participants, especially those aged between 18-25 and 36-50 years. Men, particularly in the 18-25 year age bracket, also rate the system as 'Extremely useful' or 'Useful'. This suggests a high appreciation for MOQA's applications in a domestic setting, where perhaps the integration of technology into daily routines is increasingly accepted and expected. In the workplace, the perceived utility is consistent across both genders, with a notable preference among the 18-25 and 26-35 age groups, who find MOQA 'Extremely useful'. The trend decreases slightly with age, but even the oldest demographic considers the system at least 'Useful'. The main reasons the system is considered useful by respondents are depicted in Fig. 6.3.

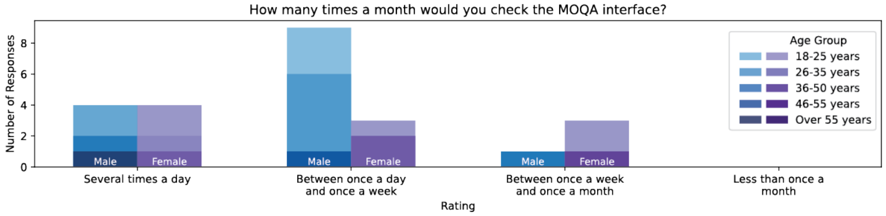
'Having an archive of data', 'receiving suggestions on best practices', 'Receiving information on how the data are collected', and 'Having data-related notifications/alerts' are deemed the most significant features that such a system should possess. The figure shows a relatively minor difference between male and female participants in terms of perceived usefulness across all functions, suggesting a general consensus on the value of these features. Age appears to be a more defining factor in the perception of the system's utility, with a noticeable variance in responses between the younger (under 35 years) and older (over 35 years) demographics. However, this difference is primarily due to the sheer number of respondents in each age group, with the younger cohort having a higher representation in the survey, which can influence the overall trend observed in the results.

Fig. 6.3 Perceived utility of the MOQA system functions.



Finally, all groups were asked how many times a month they would check the MOQA interface for an update on the IEQ and consumption of their monitored space (Fig. 6.4). The chart indicates a general trend towards regular engagement across all demographics. Variations in frequency are relatively minor, suggesting that the system's relevance spans age and gender, with most users planning to access the interface with some regularity.

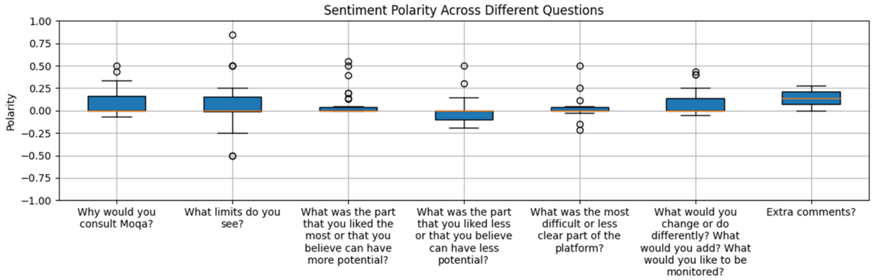
Fig. 6.4 Potential frequency of MOQA interface utilization across users.



In addition to the structured queries of the questionnaire, participants were also presented with open-ended questions, as depicted in Fig. 6.5. To extract insights from these qualitative responses, sentiment analysis [360]– a computational technique within the field of Natural Language Processing – was conducted to discern from textual data the emotions and opinions conveyed by respondents. The rationale for using sentiment analysis lies in its ability to convert qualitative feedback into quantifiable data, facilitating a more comprehensive analysis of public opinion [361]. This is particularly useful for open-ended survey responses, where the richness of free responses can yield valuable insights that closed-ended questions might miss [362]. Through sentiment analysis, sentiments expressed can be categorized as positive, negative, or neutral, affording a more profound understanding of users' attitudes towards the specific aspects of the MOQA system.

Regarding the methodology, the dataset obtained from the open-ended question was structured in an Excel file, initially in Italian, which was translated into English for effective sentiment analysis using the TextBlob library [363], a popular Python library for processing textual data. The dataset comprised several columns, each representing responses to different open-ended questions about the MOQA platform. The columns analyzed included responses to questions about the reasons for consulting MOQA, perceived limitations, parts of the platform that were most and least liked, the most challenging aspects, suggested changes or additions, and any additional comments. For each column, a sentiment analysis function to each response was applied. This function utilized the TextBlob library to calculate the polarity of each response, a sentiment metric that ranges from -1 to +1, where -1 indicates a highly negative sentiment, +1 indicates a highly positive sentiment, and 0 indicates neutrality. Figure 6.5 shows the results.

Fig. 6.5 Sentiment analysis results.



The average polarity scores mostly hover around the neutral to slightly positive range, suggesting a generally favorable or balanced perception among respondents. Notably, no column exhibits a strongly negative sentiment, indicating an absence of major dissatisfaction or adverse reactions. The main reasons for using MOQA, according to respondents, are the ability to monitor and therefore better understand their environment, but above all to optimize it, also through automation, to improve IEQ and comfort, and especially to reduce utility bills. Several users did not highlight any particular limitations of the system, understanding its flexibility and scalability; the main observations in this regard concerned the user experience with the data visualization platform, the understanding of the presented data, as well as suggestions on implementing a mobile version alongside the existing desktop application. In some cases, there is a reluctance to purchase sensors and more generally technology, despite the very limited price.

The analysis faces limitations primarily in the dataset's scope and the inherent nature of sentiment analysis. The initial idea of the study was, in fact, to merge this database with the one from the second set of interviews conducted in the context of the "Contratti di Quartiere II" project, which unfortunately were not carried out (see Section 6.2). With a limited number of responses, the results may not fully represent the diverse opinions and experiences of all potential users. Additionally, sentiment analysis, particularly using automated tools like TextBlob, can sometimes misinterpret nuances, sarcasm, or cultural context in textual responses. This method relies heavily on the quality of translation for non-English texts, which can introduce biases or inaccuracies. Consequently, while providing valuable insights, the results should be interpreted as indicative rather than conclusive and supplemented with broader qualitative and quantitative research for a comprehensive understanding.

6.4 Integration of Comfort feedback data into MOQA through OVS

The assessment of indoor thermal comfort is increasingly shifting from statistical to personalized models, leading to a growing interest in collecting feedback on occupants’ perceptions and preferences [51], [364] . Occupant Voting Systems (OVS) are therefore emerging as a widely used tool in Post Occupancy Evaluations but the level of occupants' interaction with these data collection devices, their scientific accuracy, and the integration of feedback data with building management systems, especially in residential buildings, still need to be further explored. Although the concept is not particularly recent, the term OVS was comprehensively defined by Khan et al. only in 2020 [239], referring to a system or method for collecting data on IEQ using small, user-friendly devices placed inside the building, which allow occupants to provide real-time feedback on their perceived comfort [365]. Recent advances in Information and Communication Technologies (ICTs) have made OVSs a tool often combined with questionnaires, which have always been the standard for surveying occupants' opinion [366], if not a solution to replace them. Questionnaires can assess phenomena that might be difficult to measure with sensors and gather information on large samples. However, due to cognitive biases, misunderstood or misinterpreted questions may result in erroneous reporting, and self-reported behavior may not necessarily match the observed behavior. The literature comparing OVSs and questionnaires is rather scarce [367], but it can be stated that OVSs are more efficient than surveys when the focus is on collecting complaints rather than opinions. Potentially, the benefits of an OVS are higher because the data are quantitative and continuous, which is especially useful if the goals are HVAC system tuning, integration with smart buildings, information on building operation and maintenance, and occupant comfort. OVSs are non-intrusive and more engaging for occupants, leading to higher response rates compared to a traditional questionnaire, and can be installed in easily accessible locations such as hallways or common areas. Despite these advantages, the implementation of such voting systems is so far limited to commercial or office buildings but has not yet been explored in residential environments where, thanks to the spread of smart home platforms, IoT (Internet of Things) devices, such as smart buttons and smart switches, are becoming pervasive. Moreover, the limitations of continuous subjective occupant feedback are quite well known [368]:

- Limited data on different indoor environmental factors;
- Limited flexibility compared to classical questionnaires;
- Limited feedback granularity and discrete rating scales [369];
- Technical limitations such as connectivity issues, software bugs, or hardware malfunctions;
- Usability issues: user-friendliness and right positioning;
- Engagement level over long period of time;
- Integration with building [67].

This section, resuming what was presented in [370], focuses on the methodology and results of integrating OVS data into the MOQA system. The limitations described above are highlighted by the data collected in the still ongoing monitoring of the thermal comfort of 5 public housing units in Rovigo (Italy), where smart buttons were freely available to occupants to indicate their thermal sensation. The data, although preliminary, confirmed the need for greater integration between feedback, users and building, described here in its technical component, which will be implemented in the second part of the monitoring.

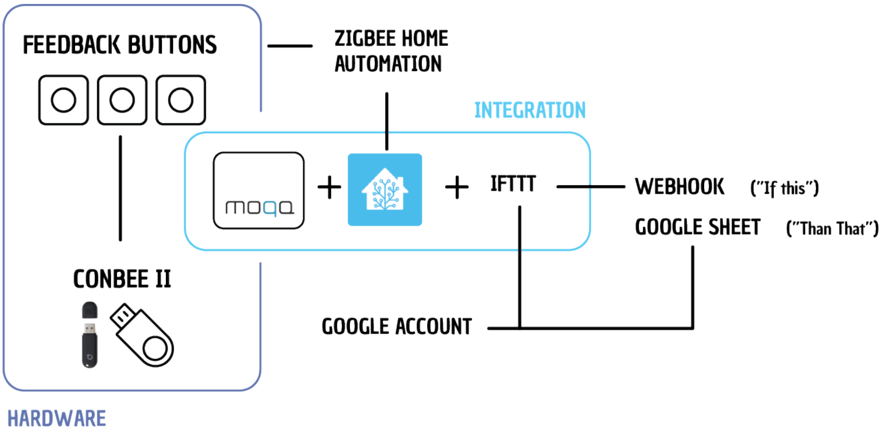
OVS architecture and case study

The OVS had to be adaptable to a variety of users – kids, adults, and the elderly – and did not require the use of technological tools such as smartphones or personal computers. In addition, the OVS had to communicate via several communication protocols - Zigbee, Z-wave, Wi-Fi, etc. - to ensure wide compatibility with environmental and energy monitoring systems or smart home platforms on the market. Attention also had to be paid to the cost of the entire system. For these reasons the concept of single-button feedback was chosen and three Zigbee smart switches were used (Fig. 6.6). These buttons are usually employed as home switches for electric lighting, but it is possible to intercept the signal they send once pressed and convert it into a trigger for custom automation.

Fig. 6.6 OVS: Smart feedback buttons

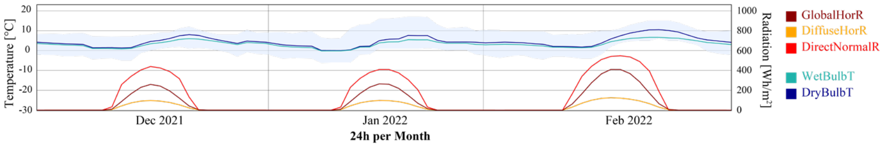
The signal is here received by a universal Zigbee-USB Dongle, mounted on the MOQA main hardware (in this case, a Raspberry Pi4) and reaches the smart home platform as "switch.turn_on" or "switch.turn_off" data. To create a backup of the system and facilitate the statistical analysis of the raw data by translating the "on-off" data into "date-time-thermal sensation", a secondary automatic procedure was implemented, aimed at creating a .csv file, then saved locally. This was done with the IFTTT (If This Than That) Web service which allows users to create chains of simple conditional instructions, called "Applets". Thus, for each physical button, an applet was created on the IFTTT Web platform that, given an initial condition ("if this"), types the desired information into an appropriately linked Google sheet ("than that"). The datetime are extracted directly from the "on-off" event recorded on the smart home platform; pressing the button indicates the corresponding thermal sensation. To properly define the "if this" condition, IFTTT services were configured on MOQA. An automation was then created to activate, through the "Webhooks" service, the applet created before every time the button was clicked (Fig. 6.7).

Fig. 6.7 OVS architecture



The research project, “Contratti di Quartiere II”, involved 5 apartments located in 3 different public housing buildings in Rovigo, Italy (45°04'25.2"N 11°47'20.3"E), built between the 1940s and the 2000s with low thermal performance. The main characteristics of the dwellings and inhabitants involved are listed in Table 6.1. The monitoring campaign is still ongoing; the analysis is here limited to the heating period of 2021-2022 (December to February). Fig. 6.8 displays monthly averages of temperature and solar radiation across the 24 hours of the day. Data were obtained from Rovigo weather station (45°03'6.2"N 11°46'28.7"E).

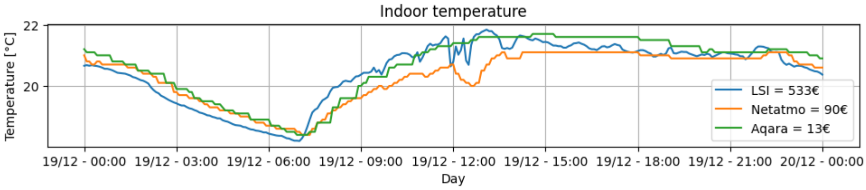
Fig. 6.8 Outdoor weather conditions in Rovigo (IT) from 12-2021 to 02-2022



OVS data

In the first phase of the study, the inhabitants were not shown any of the data collected and, except for the first presentation of the project, none of them were prompted to use the OVS. The objective was, in fact, to assess the level of interaction between the occupants and the system, without direct interference. The values measured by the indoor temperature and relative humidity sensors (Aqara WSDCGQ11LM, accuracy: ±0.3°C, ±3% and NETATMO weather station, , accuracy: ±0.3°C, ±3%) were compared with those of professional microclimatic monitoring station (accuracy: ±0.1°C, ±1%) installed in all the flats for 7 days each for calibration, confirming the validity of the measurements (see Fig. 6.9 for a daily comparison conducted in flat n.3) . Environmental data were collected every 5 minutes and at each time OVS was used.

Fig. 6.9 Indoor temperature and relative humidity measured by different sensors in the living room of flat n.3.



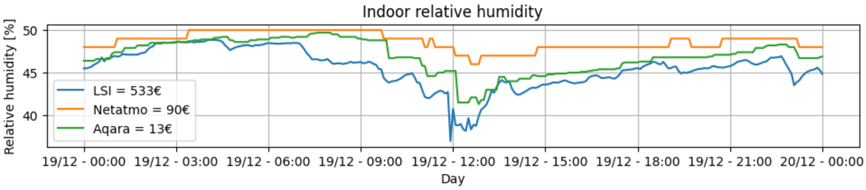
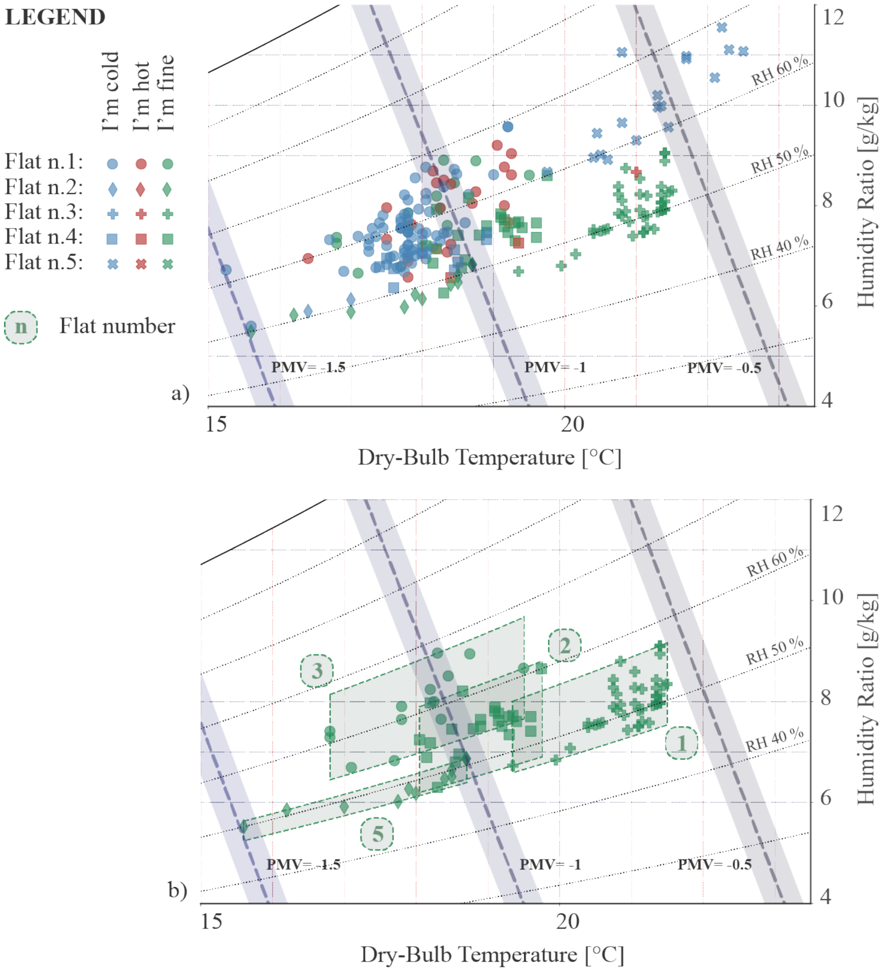


Fig. 6.10 shows on a psychrometric chart the indoor temperature and relative humidity values when the OVS feedback buttons were pressed, during the winter period 2021-2022.

Fig. 6.10 a) Psychrometric diagram showing temperature and relative humidity values - for different thermal sensations and involved households - recorded when the feedback button is pressed; b) comfort zones for different households.



In Fig. 6.10a, each shape - circle, diamond, cross, square, and filled 'x' - denotes a flat, while the color indicates the type of thermal sensation perceived: blue for 'I'm cold', green for 'I'm fine', red for 'I'm hot'. The dashed lines with colored contours represent PMV (Predicted Mean Vote) values for an air velocity of 0.2 m/s, clo=1, met=1.1, and mean radiant temperature of 20°C. These values are considered representative and/or obtained from the 7-day on-site parallel monitoring with the microclimate station (Fig. 6.11 and Fig. 6.12). The figure demonstrates that it is very complicated to define a specific thermal comfort zone when monitoring only a few environmental parameters. Data are limited as well as the people involved, but considering, for example, flat 5, it is noticeable that occupants always feel cold, even in microclimatic conditions considered good or even warm by other users. Comfortable conditions are plotted in Fig. 6.10b, which shows how comfort zones greatly differs from one household to another and how the PMV, in the figure always less than -0.5 and therefore indicating "slightly cool" to "cool" environment, cannot perfectly map the inhabitants' thermal sensations. These depend on factors that are not limited to temperature, humidity or the physical environmental parameters defined by the standards, but are also linked to the habits with which a person experiences his or her home [81].

Fig. 6.11 Trend of environmental parameters measured by the professional microclimatic station during a winter week in the living room of flat n.3.

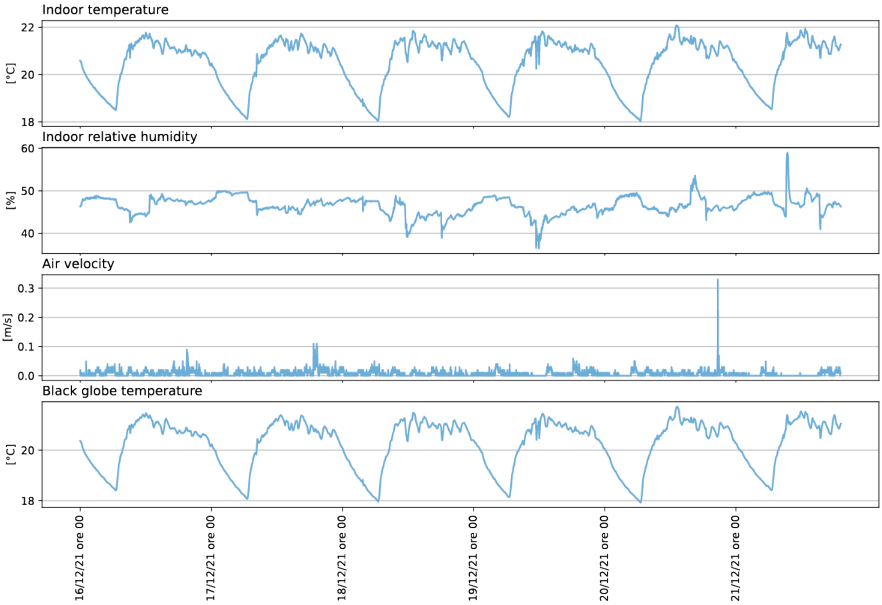


Fig. 6.12 The limited difference between indoor air temperature and black globe temperature in 4 of the 5 monitored flats.

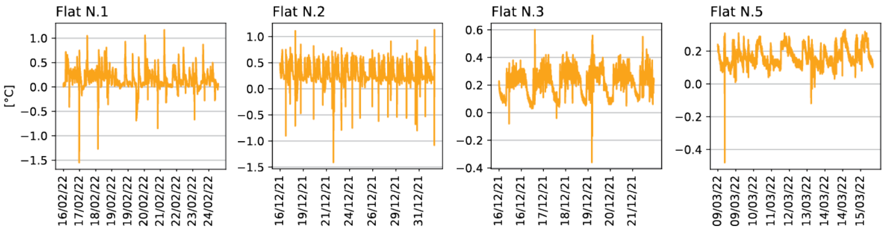
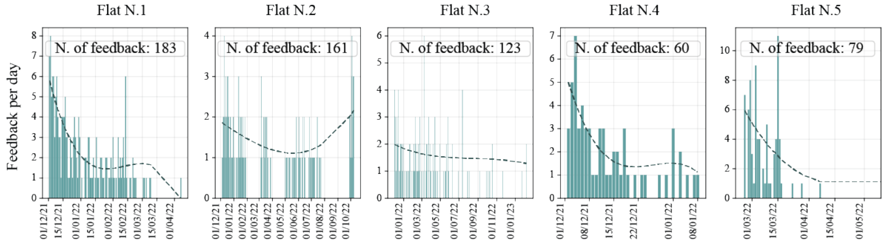


Fig. 6.13 shows the second limitation of OVS systems: the decreasing response rate over time. The five graphs, one per flat, show the trend in the amount of feedback per day. The data, in this case, is not limited to the winter 2021-2022, but extends to January 2023 to better assess the curve. As already mentioned, no reminders were given to the users involved, nor were the results of their votes shown, leaving them free to use the smart buttons, which were always placed where the user preferred (often at the entrance of the houses).

Fig. 6.13 Number of feedback received through the OVS per flat.



The total number of feedback varies among the case studies, without following any pattern related to the age or number of the inhabitants, but apparently depending on the individual's willingness to participate in the research. This decreasing level of engagement is evident in all the examined flats, except for flat number 3 where, due to technical problems, a second survey was needed in the summer, which may unintentionally have served as a reminder. However, it is not a coincidence that the number of feedback increases as the second winter season approaches. This supports the trend, already noted in the literature, that OVS is more used as a compliance tool rather than a way to testify a pleasant status.

Ways of integrating feedback data into MOQA

The project also served to develop strategies aimed at overcoming the limitations of the OVS systems described at the beginning of this Section. The main challenges in measuring comfort using discrete scales concern the definition of target values, understanding whether the same size of steps necessarily leads to equal steps in perceptions, and the need for multidimensional and multi-domain assessments [371]. New IoT technologies, such as those previously described, fully address these challenges: for instance, it would be simple to replace the thermal sensation buttons previously described with one or more physical or virtual buttons with a continuous scale (0-100%), such as those currently used for blinds controlling. It is also easy to integrate the results of surveys carried out via online platforms (e.g. Google Forms, Survey Monkey, Prolific, etc.) with which to collect metadata useful to better clarify the comfort ratings expressed via OVS. This allows for gathering information that cannot be obtained from a simple smart button, such as clothing and metabolic level. The usability problems of many OVSs are minimized by using a variety of physical or virtual feedback buttons that can be easily adapted to different users and that, given their independence from the power grid, can be freely placed in convenient locations within the living space or even worn by users. With tools such as MOQA, it is easy to collect feedback data but also to monitor environmental variables. They allow the most appropriate communication protocol to be chosen according to the case study, increasing data stability and reliability. In addition, this flexibility potentially allows cost-effective conveyance of energy consumption data, weather data, user behaviour data or any information on the Web into a single database. The OVS system, perfectly integrated with the building, can finally, if connected to a smart HVAC system, provide the necessary data to adapt the heating and cooling system's operation to user preferences.

Connecting the OVS to a smart home system can also maximize the level of occupant engagement. MOQA, for instance, displays on the IP of the main hardware on which it is running, an integrated and fully customizable graphical interface (see Section 5.2.5) where users can see their ratings, an indication of the overall indoor environmental quality of the building, as well as real-time suggestions, based on the monitored data, to improve their comfort. Furthermore, through the same platform, it is possible to implement gamification applications and send notifications or reminders to motivate occupants. In the specific context of the "Contratti di quartiere II" a bidirectional feedback exchange system was developed but, unfortunately, not field-tested due to challenges in completing the project. This system was designed to facilitate communication between MOQA and users using Telegram application. Through this system, users would send feedback or queries via Telegram, and the system would process and respond to these messages within Home Assistant. The system is also capable of communicating in reverse, with MOQA sending notifications or alerts to the user directly on the Telegram app of their smartphone. This integration, whose code is available in Appendix F, involves the creation of a bot through BotFather, integrating the bot into the Home Assistant configuration file, and creating a text entity "*input_text.telegram_message*". It also includes setting up an automation that, upon sending a message in the bot's chat activated on the user's smartphone application, stores the text of the message and the name of the person sending it (corresponding to the ID set on the Telegram application). The time of sending is also saved, in the automation entity that is automatically created. The process of sending information from MOQA to Telegram is very similar and also requires the creation of a bot and a chat. In the specific case (code available in Annex Appendix F), this procedure was not used to send notifications to users but to send daily alerts to the maintenance manager of the monitoring system regarding the proper functioning of all installed sensors.

6.5 Innovating User Feedback Collection in Indoor Environments: The Role of Wearable Technology

This section introduces an alternative method for collecting user feedback data, different from the approach outlined in section 6.3, specifically focusing on the use of wearable devices. The evolution of wearable devices in IEQ studies reflects a broader shift towards a more integrated and occupant-centric approach in building design and operation: by capturing a range of subjective and objective data, wearables offer a powerful tool for enhancing our understanding of how indoor environments affect occupant well-being [372]. Salomone et al. [373] highlight that interest in this topic is growing rapidly as well as the number of experimentations. However, the same authors stress the lack of coordinated projects, the use of closed and non-shared codes, and the absence of open-source policies. To explore the possibility of making a wearable device a useful tool for optimizing comfort and, therefore, energy use even in residential environments, reference was made to one of the few applications created to be widely disseminated in the academic environment: Cozie [344].

The Cozie app is an innovative mobile and smartwatch application designed for iOS and Fitbit devices. It enables users to provide real-time feedback on environmental conditions through micro-surveys on their Watch, collecting both physiological and environmental data. The application has already been tested by the developers and other researchers several times in the field [374]–[376]. The potential compared to a polling station or a smart button is evident: Cozie questionnaire is completely customizable, as is the number of questions. The information that can be collected is not limited to a simple "I'm hot" or "I'm cold" but includes the same data that can be gathered through a traditional questionnaire, with a significant reduction in the fatigue required for respondents.

The work presented below is the preliminary part of a broader discussion of the use of these feedback collection systems in environments other than the office or university. To understand its full potential and functionality, however, it was decided to start with the environments for which the system was originally designed. The opportunity for experimentation was provided by the recently launched M&asure Project, which focused on the environmental and energy monitoring, through MOQA, of some indoor spaces at the University of Trento. Although the type of building was similar to those already presented in many papers where Cozie was planned to be used, in this case, the Italian context and the discussions held with the involved individuals offer an alternative perspective. The work, still very much a work-in-progress, cannot be considered exhaustive or generalizable, but through experimentation, it represents a critical examination of a system with broad potential that many depict as the future for the implementation of personalized comfort strategies.

Methodology

The M&asure Project involves monitoring eight spaces at the University of Trento for two years: 2 teaching laboratories, 1 office, 1 lecture hall, and 4 study rooms, each with more than 200 seats. The main goal of the project, in addition to providing a better overview of the energy performance and comfort of the university spaces, is to directly involve the staff and students of the University in order to raise their awareness of their environmental impact and the quality of the spaces they live on daily basis.

The variables measured differ based on the space being monitored: in the laboratories and the office, the emphasis is on tracking IEQ and the electrical consumption of key devices, while for the classrooms, the focus narrowed to thermal comfort, air quality, and the users' perception of these aspects. In this initial phase of the project, necessary to evaluate how best to proceed in combining qualitative and quantitative analysis, in addition to the installation of MOQA, 4 Apple Watches were provided to the two secretaries of the office and the two heads of the laboratories, who were available and recruited during the project presentation phase. To overcome the fact that none of the participants owned an iPhone, necessary for configuring the Cozie app, the standard configuration of the latter was optimized by connecting 5 smartwatches to a single iPhone and consequently creating 5 different IDs for the questionnaire, when usually the ratio for the correct functioning of Cozie is 1 iPhone per 1 Apple Watch. This limited the participants' ability to receive notifications on their smartphones as reminders for the questionnaire, but this limitation proved to be secondary as the goal was to evaluate the undisturbed interaction of people with the tool and to collect initial feedback on the data collection methods.

The smartwatches were made available to users for a total of 15 days during the period from September to December 2023; participants were encouraged to respond to the micro-survey three times a day, wearing the watch as much as possible. Continuous use of the smartwatch indeed ensures accurate monitoring of the environmental and physiological parameters measured by the app (particularly, for this model of Watch, heart rate). Individuals were personally trained in the use of the application, encouraged, and involved in the project. They were given the freedom to use the smartwatch at their discretion, without any obligations, rewards, notifications, or alerts, and their final impressions were gathered through an informal interview. The results, in this instance as well, cannot be broadly generalized due to the small number of participants involved; however, they provide valuable insights for reflecting on the project's development and its potential application in various other contexts. For the sake of brevity, the following paragraph presents only a selection of illustrative graphs focusing on the conducted analysis of perceived thermal comfort, opening a discussion that centers less on the technical validity of applications like Cozie or MOQA, and more on the potential of the collected data to become a practical tool for optimizing building environments, including residences, where the aim is to align with user preferences and achieve reduced energy consumption.

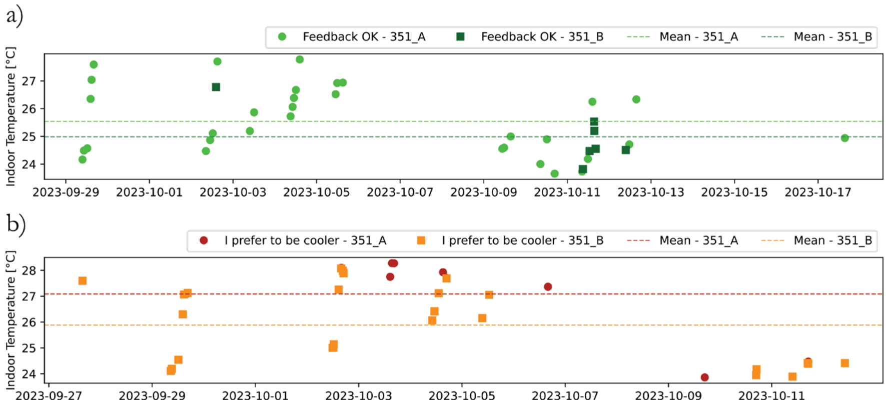
Preliminary results and discussion

Figure 6.14 shows the trend of indoor temperatures in the 3 analyzed rooms at the time of submitting the micro-surveys, represented by dots of different colors depending on the thermal perception. Fig. 6.14a refers to the director's office, where there are two secretaries, Fig. 6.14b to the photography laboratory (1 user), and Fig. 6.14c to the history laboratory (1 user) of the Department of Humanities at the University of Trento.

Fig. 6.14 Indoor temperatures in Office 351 (a), Photography Lab 238 (b), and History Lab (c): dots represent thermal feedback from the micro-survey conducted with Cozie.
Each dot aligns with the specific time the survey was completed and reflects the corresponding temperature recorded at that moment

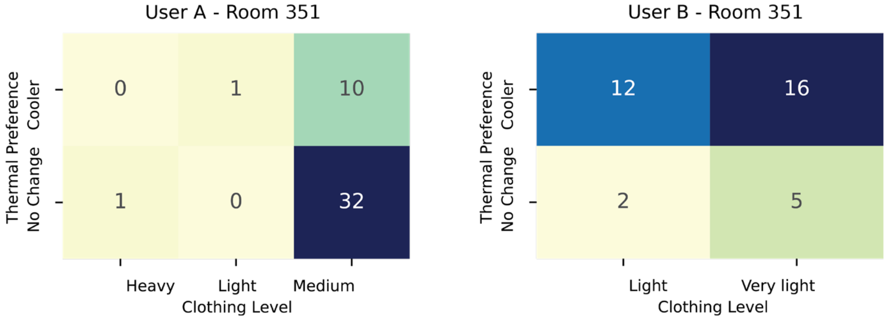
The correlation with indoor temperature is rudimentary and is a general benchmark: a thorough assessment of thermal comfort cannot be limited to this aspect. However, the interest, at this stage, given the scarcity of data, is not directed towards the correlation between perceived comfort and a specific environmental parameter, but towards the user's interaction with a new data collection device and the possibility of using it in the future as an integrated system in MOQA to couple subjective and objective evaluations. The case of the director's office, however, offers the opportunity to observe how, even under perfectly identical spatio-temporal conditions, the thermal preference between two people of the same gender and similar age can still differ (Fig. 6.15).

Fig. 6.15 Thermal feedback from the two office 351 users: "No change" (a) and "I prefer to be cooler" (b) Each dot aligns with the specific time the survey was completed and reflects the corresponding temperature recorded at that moment



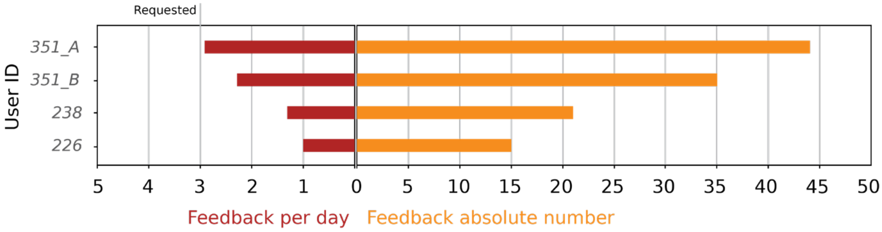
User A, represented by dots, is generally more satisfied with the environment and accepts a wider range of temperatures, while User B, indicated by squares, seems, from the limited data available, to be more sensitive to cold. This is also confirmed by the lack of correlation between the level of clothing – data also collected through Cozie - and the expressed thermal rating. In this case, heavier clothing does not correlate with a desire for a cooler environment (Fig. 6.16).

Fig. 6.16 Correlation between clothing level and thermal preferences for the two Office 351 users



The data are very limited and are reported more for information and to highlight the potential of combining Cozie with MOQA (integration code available in Appendix C), rather than to assert a scientifically valid conclusion. The scarcity of available data is one of the main points of reflection, however. Fig. 6.17 highlights the number of questionnaire responses in absolute terms and in relation to the duration of the experiment for the four people involved.

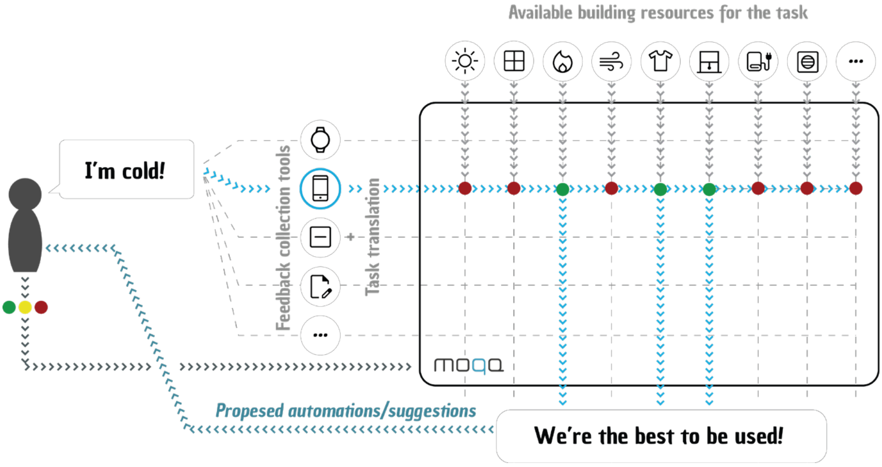
Fig. 6.17 Number of feedback received through Cozie in 15 days of campaign



Hypothetically, the feedback collected through Cozie, or even through a smart feedback button, contains information that, if correctly channeled towards the building's resources (see Section 4.3.3), could allow these resources to adapt to improve comfort and energy use, or a management system like MOQA to suggest to the user how to adjust them. However, two key questions remain open: how to channel this information and whether this information is consistently transmitted. For the first aspect, MOQA has been primarily designed for this purpose, acting as a single large "home brain" able to receive and send information from as many sources as possible: the user sends a preference through a smartwatch, a button, the room thermostat, a questionnaire, and MOQA potentially responds by suggesting which resource to modify (the shading system, the boiler, the window, the ventilation) or by automating its operation.

The real challenge, however, lies in the consistency of this exchange of information, both from the user to MOQA and from MOQA to the building. While the latter step is purely a technical and technological issue, the transfer of information from user to machine depends heavily on the level of user engagement and the ease with which they can send the data. The use of apps, smartwatches, polling stations, and smart buttons certainly represents an improvement in this regard, but their reliability over time and their ability to become ingrained in people's minds as tools for managing the building have not yet been scientifically proven. In the future, for example, the experience of thermal discomfort should not translate into a direct modification of the HVAC system's set-point, but if this discomfort is potentially reported to the smart hub, through the user's preferred tool, it would then be the hub's responsibility to channel the information towards the most convenient resource to modify, not necessarily the HVAC system (Fig. 6.18).

Fig. 6.18 The flow of information from the user to the smart hub – and building resources – to the users



The loop could be completed, in this constantly user-supervised system, by the user himself who, even using the same initial feedback tool, can inform the smart hub about the effectiveness of its decision. It is almost automatic today to think that all this could easily become the routine task of a generative artificial intelligence algorithm that could evolve into the central processing unit of the smart hub and into a '*home assistant*' in its essential form.

6.6 Main outcome and concluding remarks

This chapter has provided a detailed examination of MOQA's deployment in various settings, showcasing its adaptability and effectiveness in different contexts. The exploration encompassed multiple case studies, each offering unique insights into the system's capabilities and user interactions. MOQA has emerged as a technically innovative and minimally invasive tool for analysing and optimizing building performance. Its key features - low cost, ease of installation, support for various sensors and devices, and adaptability to different environmental variables - have been confirmed through the case studies and are in line with the guiding principles outlined in Section 5.1.

However, challenges remain in terms of its widespread acceptance and application: the research highlighted the need for continued efforts to enhance user acceptance and to scale the system's deployment effectively.

The chapter delved also into user perceptions, exploring their views, usability experiences, and interest in the system. The analysis employed both qualitative and quantitative methods, albeit limited in number due to the experimental nature of the research. Initial impressions are encouraging, especially when compared to traditional analysis tools. However, the full potential of MOQA in terms of not just monitoring indoor environments but also suggesting improvements and guiding building operations remains to be fully tested. The ongoing research endeavours, while still in progress, underline a significant effort towards leveraging MOQA's capabilities beyond mere monitoring.

7 MAIN OUTCOMES AND CONCLUSIONS

"Your work is going to fill a large part of your life, and the only way to be truly satisfied is to do what you believe is great work."

STEVE JOBS

The following sections outline the key findings in relation to the research questions, exploring their implications across scientific, industrial, and social domains, addressing limitations, and presenting potential directions for future research opportunities.

7.1 Main findings

Based on preliminary research activities that resulted in the development of a new perspective on the topics of indoor comfort and energy use in residential buildings, and informed by the case studies addressed during the doctoral program, answers to the research questions presented in Section 1.5 are outlined below.

Can we really understand energy and comfort occupant preferences and building performance using IoT and smart home platforms?

The starting point when dealing with residential buildings is to reflect on the very concept of home and its private, secure, and individualistic nature. Each of us has a unique relationship with our dwelling, with different expectations for the space where we spend most of our time and varying preferences for its configuration, functionality, and aesthetics. In addition to these subjective preferences, there is the need to ensure an adequate level of indoor environmental quality and a reduced or at least appropriate energy consumption. It is thus crucial to consider the personal relationship between occupants and their homes, which has a direct impact on the aforementioned levels of performance. One solution may be to pre-identify specific types of individuals (referred to as "personas") for whom to design and customize IoT and smart home systems for monitoring and optimizing building behavior, either more or less standardized.

The research has demonstrated the effectiveness of new, less invasive, and even wearable data collection methodologies that can communicate directly with users. However, when addressing comfort and home, direct contact with users through interviews and focus groups remains essential. As discussed in Chapter 2, the concepts of comfort and energy usage remain multifaceted and tied to experiences, habits, and personal patterns. If the goal is to alter these habits toward optimizing human-building interaction and its environmental impact, it is necessary to first delve into the underlying issues, which can only be understood through an exchange of opinions with occupants.

In any case, we cannot expect to introduce new technology or, more broadly, a new solution - such as the smart home for understanding user preferences - and hope for immediate acceptance by users. The change, especially in residential environments given their individual nature, is gradual and alternates between automatic and intentional phases. The acceptance process begins with an initial stage of ignorance, which, only if the benefits of the solution are clear or adequately explained, leads to an automatic learning process that concludes with the spontaneous implementation of the newly optimized solution (Fig. 4.1).

How might IoT technology be used to improve comfort and reduce energy consumption in residential buildings?

It is commonly recognized that IoT can significantly improve home energy efficiency: through smart thermostats adjusting temperatures, smart lighting that adapts to occupancy, environmental sensors regulating HVAC and optimizing indoor space conditions, through smart meters that identify and mitigate energy waste. Leveraging IoT facilitates collecting a vast amount of data, not only from technological devices but also through direct user interaction: in this context, new smart home technologies can expand monitoring to more buildings and individuals, retrieving data from traditionally unexplored data sources (*collaborative data mining*).

However, optimizing comfort and consumption in residential buildings requires more than monitoring devices and systems, necessitating a focus on the interaction between technology and end-users. This is particularly relevant in residential buildings where occupants may exhibit minimal interest in design or management matters, prioritizing efficient task execution.

The requirements, preferences, and general well-being of residents should come first when putting smart home solutions into practice. Installation of monitoring and automation systems is not always necessary and may even be counterproductive if not understood and accepted by users. Technology should operate seamlessly in the background with minimal oversight, and user interfaces should be straightforward. Users should have the ability to override systems, especially in emergencies, and systems should possess sufficient flexibility to handle unforeseen changes.

In a residential setting, IoT and smart home platforms should act as tools facilitating communication between the building and users, allowing them to access building's resources quickly and intuitively, optimizing the environment based on their preferences and energy efficiency considerations.

Is the collection of such data always effective?

In addressing the question of whether collecting data in the built environment for the optimization of comfort and energy consumption is always effective, the answer, according to the research, is no. Several aspects, however, need consideration within this framework.

While the contemporary landscape is inundated with an unprecedented volume of data, it is imperative to recognize that the main obstacle is wisely managing this large dataset. The process of discovering patterns and insights from large and complex data sets, while ostensibly essential in a data-rich environment, presents complexities that extend beyond its primary objectives. Interoperability challenges in the built environment further compound these difficulties, underscoring the need for a blended approach to data collection and use in the built environment.

Frequently, in fact, data collection endeavors in this domain are oriented towards the production of reports and visual representations rather than delivering tangible value, raising pertinent questions regarding the intrinsic worth and practical application of such extensive datasets. Monitoring of comfort and energy consumption requires a more thoughtful and strategic approach. Research experiences have indicated that, in relatively stable environments, like residential spaces without intricate control systems, periodic spot monitoring could become a pragmatic and resource-efficient strategy. The development of plug-and-play systems, exemplified by MOQA, specifically addresses this need through their non-intrusive design and ability to operate seamlessly after a simple electrical connection. By avoiding the pitfalls of interoperability and prioritizing a user-friendly interface, these systems offer a promising way to address the multifaceted issues associated with data collection in the built environment by transmitting data with real value to the end user, the true consumer of energy and the primary stakeholder in improving indoor environmental quality.

If further summarized, the findings of this doctoral research would be as follows:

- If interested in quantitative aspects, it is advisable to limit the analyses to IEQ. **Comfort is much more subjective than currently asserted** by regulations and technical standards.
- If the aim is to monitor IEQ, continuous monitoring is the most appropriate choice. However, if the goal is to monitor comfort, it would be better to allow users to freely express their preferences whenever they feel it is appropriate: **it's not automatic that every situation is inherently linked to a perceived and measurable level of comfort**; rather, there must be a reason or stimulus that captures the individual's attention and triggers a sense of (dis)comfort (see Section 2.1)
- **Traditional monitoring systems can be easily replaced**, for most IEQ measurement parameters, **by smart home technology** systems, which are less expensive, less invasive, more flexible, and currently almost equally accurate.
- **Smart home systems can represent an intersection between the researchers' need to obtain information on the comfort-energy use relationship in residential buildings and the need for these data to be useful** not only for the publication of academic articles but also to inform citizens and occupants on this topic.

7.2 Impacts on academia, industry and society

The research has significant potential in different fields.

From an academic perspective, the research offers a new insight into optimizing comfort and energy use in residential buildings, introducing an innovative concept – the "*resourcient*" building – which may lead to future methodologies and practices. The research results in the development of a tool – MOQA – capable of replacing traditional monitoring systems and assisting in complex research by swiftly synthesizing information from different databases, providing summaries, and identifying research gaps.

The scalability and replicability of the work can be observed both in the inherent characteristics of the developed tool and in its field application. MOQA is scalable and replicable from a technical standpoint because it is based on open-source code. The source code is made available in appendix C and D to anyone interested in continuing the experience or developing a solution based on this technology. Moreover, MOQA is replicable because it is easily installable, user-friendly, suitable for various applications, and capable of measuring nearly infinite parameters without relying on a specific sensor or data source (see Chapter 5).

At the industry level, with extensive testing already completed, MOQA presents a compelling case for transformation into an innovative startup. Its proven capabilities can attract investors and partners interested in cutting-edge technological solutions. By continuously evolving and incorporating the latest in AI (Artificial Intelligent) research and technologies, MOQA can be scaled to meet the specific needs of various industries, ranging from healthcare and finance to education and retail.

The three years of doctoral studies provided an opportunity to embark on this industrial path through attending different courses related to research-industry technology transfer, business plan development, and marketing and communication. In the development of MOQA, direct engagement with four recently established companies with similar characteristics and goals proved significant: Energenius (https://www.energenius.it/), UpSense (https://www.upsens.com/), Climify (https://climify.com/), and SmartDomotics (https://www.smartdomotics.it/). This comparison not only helped to verify and validate the developed monitoring and automation system, but also to realize that the technological aspect is just one facet to consider when aiming to bring a product to the market. The key factors are the teamwork cohesion and the passion individuals bring to their work.

Finally, from a social perspective, the research and its outcome - MOQA - have the potential to support and enhance the dissemination of information related to quality of life and energy consumption in the built environment, collecting and presenting real-time energy and environmental data in different contexts. From a more comprehensive standpoint, through the analysis of patterns and trends from diverse data sources, MOQA can provide insights into cultural and social dynamics, contributing to policymaking and social initiatives. The aspiration is that introducing such flexible and non-invasive tools into homes and, more broadly, indoor private spaces can ultimately foster a more informed society regarding energy and quality of life issues.

7.3 Limitations

Results presented in this research need to be interpreted considering some limitations.

The proposed theoretical model, which forms the basis for the development of the thesis outcome - MOQA - in residential settings, encounters challenges when extended to office environments. Offices inherently possess distinct characteristics, defined schedules, occupancy levels, workstations, and well-defined tasks, aligning more easily with personalized comfort models described in the literature rather than the proposed model. In addition, the absence of direct accountability for energy bills and a general disregard for the environmental quality of spaces perceived as non-personal significantly influence the interaction with this type of buildings and their resources.

The most substantial limitations, however, concern the application and validation of both the model and the MOQA tool it has generated. Although these challenges have been already addressed in the respective chapters, a concise summary is presented here.

The deployment of the developed monitoring and automation system, despite being built on a limited budget, extended to various contexts, but has encountered evident difficulties. The installation of a technological system demands time, costs, energy, and maintenance efforts, conflicting with the imperative of scientific research to obtain statistically robust and potentially indisputable data. The doctoral efforts invested in conceiving, developing, and optimizing the system, combined with project delays and extended timelines, resulted in a lack of structure in the results concerning the tool's validation, limited to interviews and questionnaires. The validation of the MOQA interface, for example, restricted to the 50 individuals who answered to the questionnaire and interacted directly with the platform, offers a somewhat limited and sectoral perspective, particularly given the high participation of individuals primarily under 35 years old. The subjective nature of the user experience could be assessed differently with a more diverse sample, including older participants. Due to time, cost constraints, and unforeseen circumstances such as the COVID-19 pandemic, it was not possible to validate beyond the monitoring capabilities, which proved effective, the potential of the system in terms of automation, suggestions, and optimization of comfort and energy use. While qualitative feedback on the former aspect was positive, the reduction in energy consumption could not be corroborated with field campaigns providing comparable data to the pre-existing conditions. Moreover, people's collected opinion about the system, limited to a few interviews and focus groups, cannot be generalized.

In terms of broader limitations in the utilization of the proposed system, the research has underscored several points to consider for future investigations. These factors, mirroring the reasons behind a limited adoption of smart home systems for monitoring and optimizing comfort and consumption, can be categorized as follows:

- Economic factors. Economic considerations play a crucial role: the initial and maintenance cost of these systems are not clearly defined, especially when evaluating these costs against the actual savings or building quality improvements resulting from their installation. The proposed MOQA system, however, highlights the potential use of different hardware, devices and sensors, facilitating the reuse of technologies that may no longer be in use or initially intended for other purposes. This circular approach allows for the reuse of deployed technology, even after the end of monitoring and optimization campaign, with an impact on the initial return on investment.
- Technical considerations. Even though the suggested system's wiring and installation have been optimized to be relatively straightforward, the initial technical choices regarding variables and parameters to

monitor and optimize, and their relation to the building under investigation, present challenges. Each residence is a unique case, with distinct characteristics, as are the individuals inhabiting them. Crafting appropriate suggestions or automations is a process that still requires the expertise of a technician and is extremely difficult to generalize. Optimizing the comfort and indoor environmental quality of a home is potentially easier than succeeding in reducing energy consumption. Much depends on the starting conditions: if the occupant's behavior is already energy intensive or the performance of the dwelling is inadequate, the situation is technically easier to improve. In contrast, achieving a significant reduction in energy consumption becomes more challenging when both the dwelling and its occupants are already operating at optimal levels of efficiency.

- Environmental considerations. The construction and use of a monitoring and automation system solely for the sake of technology, as well as the generation of excessive amounts of unused and unusable data, can pose an environmentally unsustainable cost. Hence, the necessity of employing flexible, reusable, and non-intrusive technologies, coupled with the need for proper design of datasets and database.
- Social factors. Efforts are still needed to alter the general perception people have of environmental energy monitoring in their homes and to elucidate the benefits and positive prospects these activities can bring. A widespread fear among occupants is that of being spied on or judged in an environment they consider private. These fears often arise from a limited understanding of the technology and its benefits, an image of the smart home world more associated with hobbyists, and a general suspicion about the technology's energy consumption and costs. The acceptance of these systems still appears to be a highly personal and individualistic choice, mainly related to the so-called "big five personality traits": Openness, Conscientiousness, Extroversion, Agreeableness and Neuroticism.
- Political and Regulatory Considerations. The development of international standards (UNI EN ISO 52120-1:2022) and certification protocols (SRI, see section 1.1) that integrate comfort, energy optimization, monitoring and automation is relatively recent. The

regulatory framework defines the rules of the game and potential investments in this technology. Simple, clear, and dedicated rules would enable investors and engineers to plan activities and distribution of investments over time more transparently.

7.4 Future research

From a theoretical as well as an applied perspective, the study presents an extensive range of future opportunities and research directions:

Developing "*Resourcient*" building indices: While this study provided a framework for assessing people's affective relationship with indoor comfort and energy at home by introducing the concept of "resourcient" building, it is necessary to develop indices that quantitatively assess the number of "resources" available in a residential setting. These indices should assess their performance, the user's ability to understand their operation, and their accessibility, allowing for direct comparisons between "resourcient" buildings and their optimization processes.

Integrating residential building data into a comparable database: Optimization of comfort and energy consumption goes beyond data collection, requiring its systematic organization and transmission to the end user. In the residential context, comparing the energy costs or indoor environmental quality data of similar buildings can serve as the primary tool to understand if the building needs intervention and simultaneously communicates to inhabitants the potential outcomes of monitoring and optimization. Thus, further exploration of the "*resourcient*" building concept through additional case studies and indoor settings is essential.

Integrating Large Language Model (LLM) Artificial Intelligent models into residential environmental monitoring and optimization systems: LLM models, recognized for their capability in general-purpose language understanding and generation, can be the crossover point between voice assistance technology, which is increasingly popular in smart homes and increasingly enjoyed by the average user, and multi-objective optimization algorithms that engineers can create tailored to a given building.

Developing an outdoor energy and environmental monitoring and automation system: Optimizing building performance also involves analyzing the surrounding context. Technologies like MOQA, utilizing widely used long-range communication protocols (e.g., LoRaWan) and portable power supplies, could adapt to monitor urban spaces and building surroundings. This integration could include devices for controlling solutions aimed at mitigating urban heat islands or broader adaptation and mitigation strategies for climate change. Initial steps in this direction have been taken during the doctoral research, with ongoing efforts to power the system from photovoltaic panels. The goal is to make MOQA highly flexible, 100% portable, and environmentally neutral, facilitating installations even in rural environments.

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APPENDIX A

List of studies included in the systematic literature review. Literature reviews, technical standards, policy articles, ten question papers, and debate papers, are excluded from the table.

Ref	*Location*	*Setting*	*Subjects*	*Results*
Climatic and environmental issues:				
[108]	UK (Coventry and Edinburgh)	Field (monitoring + surveys)	1225 students between 18 and 25 years old	The optimal acceptable temperature was higher for the warmer climatic background (24°C) than the similar/cooler climatic background groups (22°C).
[109]	China (Beijing)	Climate Chamber	8 students	Short-term thermal experience would make some excursion of real thermal sensation. In the condition that started and ended at an air temperature of 20°C, people feel more comfortable even in the 22°C environment, instead of the 25°C condition which is close to the neutral temperature in the steady state.
[110]	Global database	Data analysis on database	18966 surveys for 39 different cities and 14 different climate zones	Occupants in the location where the monthly outdoor temperature is higher than the average value 22.1 °C would result in highly significantly lower thermal sensation ($p < 0.001$); and vice versa.
[113]	Japan (Fukuoka) and Norway (Oslo)	Field interviews	18 households were interviewed	The study lists a series of contrasts and differences between the two samples in terms of heating, lighting, and hot water consumption, clothing, environmental awareness, and attitudes.

			in Oslo and 16 in Fukuoka	
[114]	Japan and the Netherlands	Field interviews	6 families in Japan, 60 Dutch households	The study investigates the differences between the two samples in their ways of dealing with staying warm at home.
[115]	India	Field (monitoring + surveys)	300 occupants (100 per climate zone)	This study, after developing 3 different thermal equations for the 3 different analyzed climate zones, concludes that it is not possible to obtain a generalized thermal comfort model for all climatic zone because adaptation process, expectation and perception of people are region specific and governed by local socio-cultural requirement.
[116]	India	Data analysis on database	17569 records	Temperature ranges calculated using Griffith's methods differed significantly with the international standards like ISO 7730 and EN 15251 considering different types of buildings, ventilation mode, seasons, etc. Although the author stated that these differences are mainly attributed to seasonal, climatic, and social-cultural dimensions of thermal adaptations there are no quantitative results in these terms.
[117]	India (Hyderabad)	Field (monitoring + surveys)	3962 records with a total of 113 respondents	The subjects were found comfortable between 26.0 °C and 32.5 °C, which was found to be much higher than the range specified in the Indian Codes (23–26 °C). This finding has enormous energy implications. Anecdotal and descriptive responses on thermal preferences are also presented.
[120]	Malaysia (Perak)	Field (monitoring + surveys)	200 occupants	The unified adaptive Fanger’s model has integrated the adaptive theories into Fanger’s model and a new unified thermal comfort model is synthesized. The model provides a widened allowance for PMV value which is ±1.17 for 80% satisfaction from the normalization of individual thermal sensation votes distribution.

[122]	Australia (Darwin)	Field (monitoring + surveys)	69 respondents	Although the mean indoor environment was above the NatHERS acceptable level, the level of thermal comfort of occupants in 6 to 7 star rated houses in the naturally ventilated mode was relatively high due to low clothing insulation, survey participants were wearing light summer clothing (0.3 clo) and in some houses, fans were switched on at high speed, creating an indoor air velocity of 1.1 m/s.
[125]	China (Ganzi Region)	Field (monitoring + surveys)	150 occupants	Based on the comprehensive analysis of the questionnaire survey results and PMV–PPD evaluation results, the design range of the indoor temperature of dwellings in Ganzi should be 10–14 °C. Thermal satisfaction can be achieved through the combination of lifestyle, activity path, and functional layout factors.
[127]	Chile (Bio-Bio region)	Field (monitoring + surveys)	121 occupants for a total of 709 records	90% acceptability provides a basic adaptive comfort limit ranging from 14.58°C. 13°C should be considered as the lowest tolerable limit during winter.
[128]	Nepal	Field (monitoring + surveys)	108 houses for a total of 275 respondents	The percentage of people reporting their environments to be in the "comfort zone", which is assumed to correspond to the central 3 categories of thermal sensation vote, is 76.8%, 82.6% and 84.7% in the cold, temperate, and sub-tropical regions, respectively. The mean comfort temperature in the cold region was 13.8 °C, which is 4.1 °C and 9.3 °C lower than that in temperate and sub-tropical regions. The mean clothing insulation in the cold region was 1.63 clo, which is 0.31 clo and 0.48 clo higher than in the temperate and sub-tropical regions.
[129]	Switzerland	Field (monitoring + surveys)	190 respondents for a total of	People from the Tropics and Subtropics were generally more tolerant towards the indoor environment than people from colder countries. The influence of climatic background and of the duration of residence in the country is not substantial when the building performs very poorly (>55% of dissatisfied). On

			40 different nationalities	the contrary, they appear to produce an effect when the building thermal performance becomes more acceptable (67%(±5%) of satisfied and neutral opinions)
[131]	Japan (Tokyo)	Field (monitoring + surveys)	406 records	Significant differences in neutral temperature were found between occupant groups of "Japanese male–non-Japanese males" ($P<0.01$), "Japanese females–non-Japanese males" ($P<0.01$), and "Japanese females—Japanese males" ($P<0.05$). The largest difference was observed between Japanese females and non-Japanese males, reaching 3.1 °C.
[132]	China	Internet-based survey	1140 subjects	Thermal sensation in northern areas of China is dominated by neutral and hot side votes (79% for N–N group (subjects who had always lived in northern China), 89% for N–S group (those who had moved from northern China to southern China), and 94% for S–N group ((vice versa)). Meanwhile, most occupants in southern China felt cold or cool (74% for N-N group, 75% for N–S group, and 94% for S–N group). People who experienced both un-conditioned (southern area) and very comfortable (northern area) indoor climates expressed much more positive evaluations of the northern region along with much more negative evaluations on the southern region.
[136]	UK	Field (monitoring + surveys)	427 households (390 monitored)	Many English households choose living room and bedroom temperatures below than those anticipated by the BSEN15251 standard. The proportion of cool homes was greater in the cooler areas of the country, such as Yorkshire and the North East, than in the other, warmer areas. Since the adaptive standard accounts for differences in ambient temperature, this result suggests that the occupants of cooler regions are more tolerant of cool indoor temperatures than those living in warmer regions.
[137]	European database	Data analysis on database	1320 records	There are statistically significant differences in terms of Thermal comfort between users in different countries. Please refer to the article for the large number of supporting quantitative results

Age:				
[130]	China (Shanghai)	Field and climate chamber (monitoring + survey)	1040 occupants (field); 18 people (climate chamber)	Data analysis and machine learning allow authors to create a new thermal comfort model for elderly whit an overall prediction 24.9% higher than the prediction accuracy of the PMV model
[140]	Spain (Madrid)	Field (monitoring + surveys)	413 people	Thermal comfort ranges for older adults in public spaces in Madrid would be in winter 18.49–21.51 °C; in spring 15.88–21.92 °C; summer 23.89–28.31 °C and in autumn 17.86–22.08 °C. Although older people perceived the thermal environment as comfortable, according to PET and UTCI indices, they would be at risk of thermal stress all year, especially in summer and winter.
[143]	Poland (Warsaw)	Field (monitoring + surveys)	818 records	The older respondents less frequently wished warmer weather ($C = 0.188$; $p = 0.002$)
[144]	Hong Kong	Field (monitoring + surveys)	454 records	The effect of age is also significant during the summer and has a negative impact on the elderly's thermal comfort (estimate = -0.221, $p < 0.05$). With the increase of age, elderly people are more likely to feel less thermally comfortable during the summer in Hong Kong.
[147]	South Korea	Internet-based survey	3245 households	Age is probably less important in determining consumers' household energy involvement than are their personal values and preferences
[152]	USA (Elizabeth)	Field (monitoring + interviews)	144 records	There are high percentages of dissatisfaction in all sites regarding the indoor air drafts, feeling of stuffiness and extreme humidity, while half of the sample also reported feeling uncomfortably warm during summer. Residents reported using less A/C during heat waves and more window opening, while the use of fans remained the same. Leaving the apartment happens less, as expected, and the same counts for clothing adjustment.

[153]	Denmark	Internet and phone-based interview	1216 respondents	The results suggest that conventions and expectations of comfort do relate to social group differences, where social groups (e.g. educational groups, age groups, and gender) have a different understanding of the importance of comfort and comfort expectations. People older than 65 years tend to value comfort more highly in general, although the estimate is not strongly significant
[154]	Chile (Santiago)	Field (monitoring + surveys)	2946 respondents	Children tend to adapt to indoor temperatures, with mean comfort temperatures derived from their thermal sensation vote being as low as 15.6 °C – 14.8 °C – 14.7 °C in winter and 22.5 °C – 23.1 °C in spring, depending on the estimation method. Children that come from deprived environments tend to adapt to lower temperatures better than those who come from less deprived ones.
[157]	China (Beijing)	Field (monitoring + surveys)	54 occupants	Elderly occupants exhibited the strongest thermal sensitivity to indoor air temperature changes, yielding a slope of approximately 0.44/°C, followed by young occupants with a slope of approximately 0.41/°C. In comparison, middle-aged occupants were far less sensitive to changes in indoor air temperature than the elderly and young occupants, with a regression slope of only 0.28/°C. In other words, for middle-aged occupants, a shift of one unit of thermal sensation on the ASHRAE 7-point scale would occur with a change in indoor air temperature of 3.57 °C, whereas for the young and elderly occupants, changes of only 2.44 °C and 2.27 °C in indoor air temperature, respectively, would be required.
[173]	US database	Data analysis on database	924 individuals	Age has a significant effect on the heat production of all activity conditions, and boys always produce more heat than girls, except for walking at 4.8 km/h where there is no significant difference between genders due to the smaller sample size. The heat production of boys continues to increase with age, while that of girls reaches its maximum at 13–15 years old and slightly decreases from

				16 to 18 years old, except for cycling at 16 km/h, where it continues to increase.
Gender:				
[110]	Global database	Data analysis on database	18966 surveys	Occupants' thermal sensation is significantly different between males and females ($p < 0.01$), and males tend to perceive the same thermal environment 0.10 unit warmer than their female counterparts. Thermal sensitivity (interaction item between gender and air temperature) is also highly significantly different between different genders ($p < 0.001$)—thermal sensitivity of males (0.322) is significantly lower than that of females (0.352), meaning that it takes males 3.1 °C higher or lower air temperature to change one unit of their thermal sensation vote compared to 2.8 °C of air temperature for females.
[131]	Japan (Tokyo)	Field (monitoring + surveys)	406 records	Significant differences in neutral temperature were found between occupant groups of "Japanese male–non-Japanese males" ($P<0.01$), "Japanese females–non-Japanese males" ($P<0.01$), and "Japanese females—Japanese males" ($P<0.05$). The largest difference was observed between Japanese females and non-Japanese males, reaching 3.1 °C. The Japanese females reported more dryness compared to non-Japanese males under 55% RH.
[153]	Denmark	Internet and phone-based interview	1216 respondents	Women in general value comfort more highly. Men and women might perform different practices in the home and might relate differently to the concept of home and thus to the importance of comfort.
[157]	China (Beijing)	Field (monitoring + surveys)	54 occupants	Female occupants were observed to be slightly more thermally sensitive than male occupants, which was reflected in a slope for female occupants of 0.39/°C (approximately 0.05/°C higher than that for male occupants).
[159]	Brazil (Florianopolis)	Field (monitoring + surveys)	7564 surveys	Male occupants are 2.31 times (OR = 2.31) more likely to express 'warm discomfort' than female occupants. Females are 2.33 times (OR = 0.43 for males, i.e., OR = 1.00/0.43 for females) more likely to declare 'cold discomfort'

				than males. Females have a lower metabolic rate and a lower skin temperature than males, thus, females prefer warmer conditions than males.
[160]	Bahrain	Field (observations + surveys + interviews + simulation)	111 surveys	In Bahraini society, gender segregation is practiced extensively both in homes and in public. The case study highlights the importance of family privacy, and it is divided into different zones for both males and females. This would allow family members, in particular female members, to use the outdoor space more often. No females were interviewed.
[161]	UK	Field (monitoring + interviews)	427 interviews, 387 monitored homes	Women who express a greater belief strength that using less heating has a higher impact on thermal comfort tend to have their central heating on for a longer time periods. The results correspond to previous research which has demonstrated that females preferred higher indoor winter temperatures to keep thermal comfort than males
[162]	USA	Surveys	494 single-occupant males and 786 single-occupant females	The differences between men and women are small and statistically insignificant except for in reported nighttime heating temperature, which is 0.26 °C [0.47 °F] higher for non-single-occupant individuals. For single females (males), 41% (46%) report setting one heating temperature and not adjusting it during the day, 30% (27%) report manually adjusting the heating temperature during the day, 16% (13%) report using a programmable thermostat to change the heating temperature, and 11% (13%) report that they turn off the heating equipment to change the heating temperature during the day. For cooling the findings are similar. Given the popular narrative that thermostats are set too low for females' preferences, the differences in mean reported thermostat settings between single-occupant males and females are surprisingly small (less than 0.3 °C [0.5 °F] at most).
[172]	China	Climate chamber	40 subjects	or Thermal Sensation Vote, statistically significant gender differences are found at 14 °C ($p < 0.01$), 16 °C ($p < 0.05$), and 18 °C ($p < 0.05$). There are no significant gender differences in the comfortable zone (24°C and 26°C)

[173]	US database	Data analysis on database	924 individuals	Age has a significant effect on the heat production of all activity conditions, and boys always produce more heat than girls, except for walking at 4.8 km/h where there is no significant difference between genders due to the smaller sample size. The heat production of boys continues to increase with age, while that of girls reaches its maximum at 13–15 years old and slightly decreases from 16 to 18 years old, except for cycling at 16 km/h, where it continues to increase.
[184]	India (Darjeeling)	Field (monitoring + surveys)	444 records	The difference in the Thermal Sensation Vote between the two genders was not statistically significant
[195]	Switzerland	Field (interviews + focus group)	20 interviews, 16 participants in focus groups	The authors did not notice any difference in how people physically experience heat or cold based on gender: in some cases, men felt colder than women during the challenge, and this was mostly related to habits developed over time, such as sleeping in the nude.
[208]	India (Hyderabad)	Field (monitoring + surveys)	45 apartments, 113 subjects, 3962 records	A higher percentage of women expressed comfort in home environments. While 74% female subjects voted in the central three categories of the sensation scale, only 69% men felt similarly. Mean comfort temperature of women was also found to be slightly higher than men in the monsoon season.
Body Composition and Physical Activities:				
[159]	Brazil (Florianopolis)	Field (monitoring + surveys)	7564 surveys	Metabolic rates presented a difference of 5% between genders and different age groups (females and older adults presented a lower metabolism). Females have a lower metabolic rate and a lower skin temperature than males, thus, females prefer warmer conditions than males. However, the greatest difference in the metabolic rate was noted in relation to the weight of subject, as assessed with

				the Body Mass Index (BMI): overweight subjects had a metabolic rate 30% lower than normal weight people
[160]	Bahrain	Field (observations + surveys + interviews + simulation)	111 surveys	In Bahraini society, gender segregation is practiced extensively both in homes and in public. The case study highlights the importance of family privacy, and it is divided into different zones for both males and females. Women and men, who live in different areas of the home, perform different tasks.
[172]	China	Climate chamber	40 subjects	The overall metabolic rate was lower in females than in males at all temperatures. However, the difference in metabolic rate between genders was statistically significant only at 14, 16, and 18 °C ambient temperatures. In the comfort zone (24 °C and 26 °C), the metabolic rate was the lowest for both genders. Skin temperature decreased with declining ambient temperature without a statistically significant difference between males and females
[173]	US database	Data analysis on database	924 individuals	Age has a significant effect on the heat production of all activity conditions, and boys always produce more heat than girls, except for walking at 4.8 km/h where there is no significant difference between genders due to the smaller sample size. The heat production of boys continues to increase with age, while that of girls reaches its maximum at 13–15 years old and slightly decreases from 16 to 18 years old, except for cycling at 16 km/h, where it continues to increase.
[174]	China (Beijing)	Climate chamber	31 subjects	If the subject remained sitting in the chamber for 30 min, the metabolic rate stabilized at 1.0 met, which was similar to the recommended value in the ASHRAE standard. The greater the exercise intensity, the more uncomfortable they felt. This feeling decreased once they stopped. However, if the subjects continuously remain at rest in an airtight room, they would feel more and more uncomfortable.
Clothing level:				

[128]	Nepal	Field (monitoring + surveys)	108 houses for a total of 275 respondents	The percentage of people reporting their environments to be in the "comfort zone", which is assumed to correspond to the central 3 categories of thermal sensation vote, is 76.8%, 82.6% and 84.7% in the cold, temperate, and sub-tropical regions, respectively. The mean comfort temperature in the cold region was 13.8 °C, which is 4.1 °C and 9.3 °C lower than that in temperate and sub-tropical regions. The mean clothing insulation in the cold region was 1.63 clo, which is 0.31 clo and 0.48 clo higher than in the temperate and sub-tropical regions.
[130]	China (Shanghai)	Field and climate chamber (monitoring + survey)	1040 occupants (field); 18 people (climate chamber)	Data analysis and machine learning allow authors to create a new thermal comfort model for elderly whit an overall prediction 24.9% higher than the prediction accuracy of the PMV model. Air temperature was found to be the major contributor of field study model with the highest variable importance. And it is also highly correlated with older people's clothing insulation.
[176]	Egypt (Cairo)	Field (monitoring + surveys)	787 surveys	The study limitations are related to the lack of values adopted in the ISO 9920 corresponding to items of clothing used in Egypt especially the exact values for the veil (Hijab) and Abaya. The Abaya is a traditional silk or wool loose cloak, reflecting the female religious belief, covering the whole body except for the face, palms of hands and toes.
[178]	India (Tezpur and Shillong)	Field (monitoring + surveys)	460 subjects	A big limitation of thermal comfort studies done in South Asian countries, particularly in India, are clothing insulation values of traditional dress patterns. This study faced the same limitation. Nonlinear regression analysis shows clothing related adaptation by subjects at low and high temperatures, but the maximum adaptation takes place on the cooler side of the thermal sensation scale.
[180]	Chinese database	Data analysis on database	206 respondents	The study presents a new model for predicting thermal comfort conditions in hot and humid environments. The authors demonstrated that the assumption

				of uniform clothing coverage can lead to misleading conclusions, with an average deviation in thermal sensation ranging from 0.2 to 0.45 units when wearing clothing suitable for the hot season.
[184]	India (Darjeeling)	Field (monitoring + surveys)	444 records	The clothing insulation showed a strong and significant correlation with the outdoor air temperature. The clothing insulation was found to decrease with the increase in the indoor operative temperature and vice versa. It shows that the subjects used clothing as a powerful adaptive opportunity to remain comfortable in the changing temperatures.
[188]	China (Tibetan Plateau)	Field (monitoring + surveys)	1182 respondents	Tibetan residents have a variety of traditional dress ranges all year round, such as the 'Chuba', the Tibetan-style robe, which is characterized by long sleeves, a loose waist, and large lapels. When the indoor temperature is higher than 25 °C, the clothing insulation changes slightly with a gentle slope, which is mainly within the range between 1.1clo to 0.8clo.
[206]	Australia (Brisbane)	Field (observations + surveys)	6 interviews	Clothing-based adaptive opportunities were dependent not only on workplace culture, but on the locational context, demonstrating that people take their clothing cues from influences beyond weather and workplace
Habits and ways of human-building interaction:				
[79]	South Korea	Field (monitoring + surveys)	77 occupants	Occupants with different levels of perceived control showed a clear distinction in thermal sensations (Kruskal-Wallis test, $\chi 2$ (2) = 16.828, $P < 0.001$). The mean comfort vote was 0.64 (SD = 0.95) for occupants with a low level of perceived control, whereas the vote was −0.02 (SD = 0.78) for those with a high level of perceived control.
[115]	India	Field (monitoring + surveys)	300 occupants (100 per climate zone)	This study, after developing 3 different thermal equations for the 3 different analyzed climate zones, concludes that it is not possible that thermal comfort models do not consider the importance of the various variables that controls the comfort in built environment

[152]	USA (Elizabeth)	Field (monitoring + interviews)	144 records	The most frequently reported behaviors in the baseline (all summer) and follow-up (heat waves) interviews include the use of air-conditioning as the most popular action, followed by fans, window opening and clothing adjustment. Leaving the apartment is another consideration, although, as specified in the interviews, it is not necessarily due to the indoor heat stress. Surprisingly, residents reported using less A/C during heat waves and more window opening, while the use of fans remained the same. Leaving the apartment happens less, as expected, and the same counts for clothing adjustment.
[157]	China (Beijing)	Field (monitoring + surveys)	54 occupants	Male occupants showed a higher frequency of turning on the air conditioning than female occupants. Among occupants of different ages, elderly occupants used air conditioning least frequently. In addition, the frequency of turning on air conditioning was less than 20% for all occupants in this study, demonstrating that occupants did not turn on the air conditioning immediately upon declaring the indoor environment unacceptable.
[184]	India (Darjeeling)	Field (monitoring + surveys)	444 records	During the cool months a mean of 3.66 cups (SD 3.12, N = 56, maximum 15 cups) of tea or coffee and during the warm months, mean of 1.48 glasses (SD 4.93, N 83, maximum 8 glasses) of cold beverage was observed. The greater standard deviation, especially during the warmer season represent that the subjects still took hot beverages like tea, which may not only be to provide warmth as during the cooler months but also to bring relaxation. Taking showers with cold water is one of the measures of adjustment in warm climatic condition: a mean of 1.80 times of showers per week (SD 1.40, N = 56) during the cooler months and mean of 2.52 times per week (SD 1.55, N 79) during the warmer months was observed. It was also interesting to note that during the cooler months, subjects went to bed earlier (mean 9:36 PM, SD 1.40 h, N 56) and woke up late (mean 6:18 AM, SD 1.24 h, N 56), while during the warmer

				month, subjects went to bed later (mean 9:59 PM, SD 1.26 h, N 82) and woke up earlier (mean 5:48 AM, SD 1.02 h, N 80).
[185]	Japan (Tokyo and Kanagawa)	Field (monitoring + surveys)	503 subjects	It was found that the comfort temperature changes according adjustment behavior which are mainly the change of the clothing and the control of open windows across different seasons. In addition, at much higher or lower outdoor temperature people adaptation ability will not be enough and conventional cooling or heating mechanism needs to be used to achieve thermal comfort.
[187]	Cyprus	Field (monitoring + surveys + interviews)	3 buildings, 6 subjects	Surveys showed that inhabitants were satisfied with the deliberate passive cooling, ventilation strategies and adaptive opportunities their houses provided, which combined with the thermal inertia of the building envelope, maintained indoor temperatures within the thermal comfort range for most of the year. Surveys also attested that due to the nature of their daily chores, inhabitants lived outdoors, preferring to work in shaded corners and breezeways in the courtyard.
[188]	China (Tibetan Plateau)	Field (monitoring + surveys)	1182 respondents	In summer, residents use natural ventilation to improve indoor warm/hot indoor conditions; while in winter, they usually wear more clothes, drink butter and sweet tea, or use a stove/fire heater to keep warm as their homes lack central heating systems. Butter tea is a kind of high-calorie hot drink which not only replenishes their daily requirements, but also enables people to keep warm in winter. Therefore, drinking a cup of warm butter tea or sweet tea has become a feature of the residents' lifestyle.
[189]	Turkey (Bingöl)	Field (monitoring + surveys)	100 respondents	Today's housing users link residential comfort with economic spending power. It is seen that the vernacular Bingöl houses, which are produced in accordance with the climate, are designed and built in such a way that user comfort can be achieved with the efficient use of natural energy resources.

[190]	Australia	Field (monitoring + interviews)	5 buildings	Analysis of the interviews revealed that for occupants and architects, issues related to energy and environmental performance, including thermal performance, when expressed in their own voices, were an integral but not dominant part of a holistic view of these houses, both in pre-construction aspirations and post-construction evaluations.
[191]	Portugal (São Vicente e Ventosa)	Field (monitoring + surveys)	22 dwellings	The focus group findings confirmed that the occupants' adaptive behaviors were perceived as more limited during winter, mainly encompassing personal environmental control measures, i.e. wearing additional garment layers and bed clothing for increased insulation (Table 2), hot water bottles and beverages, and environmental adjustments such as turning the heating on (86 % of case studies). The heating season, where most occupants are dissatisfied with thermal environmental conditions, had a lower level of perceived environmental control. During summer, coping strategies ranged from operating the wickets or doors for natural ventilation to mechanical ventilation with fans and sitting in outdoor shaded spaces.
[192]	Denmark	Field (monitoring + surveys)	500 respondents, 30 monitored households	The author found that technologies, embodied habits, knowledge, and meanings are the main components in the understanding of their practice. Regarding embodied habits, some of the interviewed households explain their behavior in regulating their indoor climate recalling their experience of other practices e.g., habits in the workplace or parents' habits in their childhood experience.
[193]	Jordan (Ammam)	Field (monitoring + surveys)	35 apartments	The most influencing variables on occupants' spatial behavior were their thermal satisfaction and performed activity, but also other factors such as occupants' age, outdoor temperature, parents' educational level and the availability of AC units.

[194]	Iran (Yazd)	Field (observations + surveys + interviews)	198 respondents	During the summer, for instance, occupants are used to sleep on the roof and during the daytime, they moved between the courtyard, the summer quarters, and the basement, depending on the outdoor temperature.
[195]	Switzerland	Field (monitoring + interviews + focus group)	20 interviews, 16 participants in focus groups	Heating set-point temperatures in Switzerland have changed over the past century, and solutions once used to get warm (sharing a bed, sleeping in clothes) are no longer common. Today people are used to walking around the house barefoot and in t-shirts even in winter, regardless of outdoor weather conditions.
[196]	Libya (Ghadames)	Field (monitoring + surveys)	8 buildings, 32 subjects	The findings of field surveys concerned with indoor living conditions and thermal environment showed that operational issues were preferable in old houses; natural ventilation and availability of day lighting, viability of local construction materials, indoor thermal conditions, and energy efficiency strategy were among those issues
[197]	Algeria (Menaa)	Field (observations + surveys)	10 houses, 70 respondents	85% of the respondents stated that the cold conditions in the houses led them to abandon the houses during winter. 90% respondents believed that deterioration of the interior walls, the ground and the leaking roof were the main factors that led to the thermal discomfort of these houses during winter as these houses have many openings and not fully insulated.
[206]	Australia (Brisbane)	Field (observations + surveys)	6 interviews	Behavioral adaptations, on the other hand, were found to be important, particularly the opening of windows and doors, clothing flexibility and consumption of hot and cold food and drink.
Contextual factors and socio-physiological aspects:				
[153]	Denmark	Internet and phone-based interview	1216 respondents	Women in general value comfort more highly. This could indicate that women in general spend more time at home and are more concerned with homely comfort, as directed by social structures.

[154]	Chile (Santiago)	Field (monitoring + surveys)	2946 respondents	children that come from deprived environments tend to adapt to lower temperatures better than those who come from less deprived ones.
[160]	Bahrain	Field (observations + surveys + interviews + simulation)	111 surveys	In Bahraini society, gender segregation is practiced extensively both in homes and in public. The case study highlights the importance of family privacy, and it is divided into different zones for both males and females. This would allow family members, in particular female members, to use the outdoor space more often. No females were interviewed
[204]	China	Internet-based survey	904 respondents	Most residents, 70%, adopted the most popular heating equipment in this region, including electrical heating appliances and AC. People with medium energy-consumption patterns had higher intentions to change their current patterns and to demand improvement in their indoor environment. Findings indicate that residents were concerned about the cost without realizing that their current patterns could produce high energy consumption
[206]	Australia (Brisbane)	Field (observations + surveys)	6 interviews	Negotiation systems were strongly dependent on the social context, whereby occupants were reluctant to impose their preference on others, but were more than willing to make incremental changes as needed
Income and educational level:				
[144]	Hong Kong	Field (monitoring + surveys)	454 records	The elderly who have higher educational backgrounds are more likely to have higher thermal sensation votes, such as ‘warm’ or ‘hot’ in the summer.
[152]	USA (Elizabeth)	Field (monitoring + interviews)	144 records	Residents in sites with poor envelopes engage in a wider range of adaptive actions during heat waves. Besides apartment characteristics, occupant behaviors have a significant effect on indoor thermal performance and that those behaviors vary significantly based on the resources available to the residents.

[153]	Denmark	Internet and phone-based interview	1216 respondents	People with longer (e.g. master's degree) and shorter education (e.g. elementary school) as the highest attained education tend to value comfort more highly than people with a medium-cycle education (e.g. high school and bachelor's degree).
[154]	Chile (Santiago)	Field (monitoring + surveys)	2946 respondents	Membrillar School has students from very low socio-economic backgrounds (IVE-SINAE index = 86.3%) whose comfort temperature is only 12.0 °C – 13.6 °C – 13.5 °C in winter, depending on the estimation method. República de Siria School has students from higher socio-economic backgrounds (IVE-SINAE index = 37.6%) whose comfort temperature is 16.8 °C – 16.3 °C – 16.4 °C, depending on the estimation method. The difference between both schools can be up to 4.8 K with the classic regression method.
[189]	Turkey (Bingöl)	Field (monitoring + surveys)	100 respondents	Today's housing users link residential comfort with economic spending power. In newly built houses, energy efficient and climate-balanced approach in traditional buildings are generally ignored
[204]	China	Internet-based survey	904 respondents	Family income was one of the most important factors influencing current heating patterns, followed by number of children and building construction year. Income was the mediator of the relationship between building type and current heating patterns (indirect effect)
[208]	India (Hyderabad)	Field (monitoring + surveys)	45 apartments, 113 subjects, 3962 records	Subjects in higher economic groups had lower comfort temperature than their counterparts in lower economic groups. The difference (1.2 K) is statistically significant at 95% confidence interval. Subjects in the higher economic group flats having greater and frequent access to the ACs and air coolers.
[209]	Ukraine (Stakhanov)	Field (interviews)	3000 respondents	It has transpired that a household's need to borrow money in the recent past is a much better predictor of inadequate thermal comfort than declared income levels—this may be attributed to the relative unreliability of reported income, as well as the possibility that perceived thermal comfort does not increase beyond a certain income level.

[210]	Spain (Barcelona)	Field (monitoring + surveys)	74 respondents	The environmental comfort analysis demonstrates that in general terms, Energy Poverty (EP)-affected households report worst thermal comfort and indoor air quality conditions than non-EP households. Nevertheless, reported thermal comfort perception in the wintertime is considerably worse than in EP households than non-EP.
[211]	Chile (Santiago)	Field (monitoring)	20 households	The results obtained show that economic inequality is reflected in essential aspects of life quality within households, mainly through thermal comfort.
[212]	Austria (Kerns)	Internet and phone-based interviews + surveys	19 interviews, 25 surveys	Several reasons are mentioned for being unable to heat some rooms: leaky windows and doors, insufficient or lacking insulation, old and inefficient heating system, and the technical impossibility to heat some rooms (e.g. due to lack of connection to chimney) besides economic reasons.
[213]	Ireland	Field (surveys)	1500 homes	31.6% of respondents reported an inability to pay for these measures, while a further 5.5% reported more pressing priorities for expenditure. It's worth noting that 32.3% mentioned that they were unaware of the benefits of these measures.

APPENDIX B

List of selected EU-funded projects related to the topics of comfort, energy, and smart buildings.

Project acronym	*Aim of the project*	*Project end date*	*Remaining time (Calculated from 08/2023) [■= 3 months]*	*Link*
From the research query in CORDIS [268]*:*				
4RinEU	4RinEU will define robust, cost-effective, tailorable deep renovation technology packages supported by usable methodologies, feeding into reliable business models.	30/06/2021		https://cordis.europa.eu/project/id/723829
AEGIR	AEGIR's main objective is to demonstrate a scalable, industrialised, smart, non-intrusive, quick, and affordable four-packaged renovation solution to boost the take up of deep retrofitting.	30/09/2026	■■■■■■■■■■■■	https://cordis.europa.eu/project/id/101079961
ALDREN	The ALDREN objectives are to achieve higher renovation rates and better renovation quality by overcoming market barriers and preparing the ground for investment.	30/09/2020		https://cordis.europa.eu/project/id/754159
ASSIST	ASSIST aim to tackle fuel poverty and support vulnerable consumers.	30/06/2020		https://cordis.europa.eu

				/project/id/754051
A-ZEB	A-ZEB aims to achieve significant construction and lifecycle cost reductions of new NZEB's through integral process optimization in all construction phases.	30/04/2020		https://cordis.europa.eu/project/id/754174
BD4NRG	BD4NRG project aims to develop a reference architecture for smart energy to align various architectures together with an interoperable AI-driven big data analytics framework.	31/12/2023	■	https://cordis.europa.eu/project/id/872613
BENEFFICE	BENEFFICE's strategic objective is to reduce wasted energy by incentivising various consumer types in the wide energy consumer market	30/04/2021		https://cordis.europa.eu/project/id/768774
BEYOND	BEYOND brings forward a reference Big Data Management Platform, on top of which an advanced AI analytics toolkit will be offered allowing for the delivery of derivative data and intelligence out of a blend of real-life building data and relevant data coming from external sources.	30/11/2023	■	https://cordis.europa.eu/project/id/957020
BIGG	BIGG aims at demonstrating the application of big data technologies and data analytic techniques for the complete buildings life-cycle of buildings	30/11/2023	■	https://cordis.europa.eu/project/id/957047

BRESAER	The overall objective of BRESAER project is to design, develop and demonstrate an innovative, cost-effective, adaptable and industrialized envelope system for buildings refurbishment	31/07/2019		https://cordis.europa.eu/project/id/637186
CLEAR-X	CLEAR-X project's overall objective is to help consumers reduce their energy bills by improving the energy performance and comfort of their homes through the investment in renewable energy and sustainable energy (RES), as well as energy-efficient technologies.	29/02/2024	■■	https://cordis.europa.eu/project/id/101033682
COLLECTiEF	The COLLECTiEF consortium will enhance, implement, test and evaluateimplement an interoperable and scalable energy management system to smart up buildings and their legacy equipment on large scale.	31/05/2025	■■■■■■■■	https://cordis.europa.eu/project/id/101033683
COOLTORISE	COOLTORISE project will establish a framework on summer energy poverty to define common solutions.	31/08/2024	■■■■	https://cordis.europa.eu/project/id/101032823
D^2EPC	D^2EPC ambitiously aims to set the grounds for the next generation of dynamic Energy Performance Certificates (EPCs) for buildings	31/08/2023		https://cordis.europa.eu/project/id/892984
DRIMPAC	The main outcome of DRIMPAC is to develop a comprehensive solution to empower consumers to become active participants in the energy market.	31/08/2022		https://cordis.europa.eu

				/project/id/768559
E2VENT	EVENT will develop, demonstrate and validate a cost effective, high energy efficient, low CO2 emissions, replicable, low intrusive, systemic approach for retrofitting of residential and commercial buildings.	30/06/2018		https://cordis.europa.eu/project/id/637261
enCOMPASS	The enCOMPASS project will implement and validate an integrated socio-technical approach to behavioural change for energy saving, by developing innovative user-friendly digital tools to make energy consumption data available and understandable for different stakeholders	30/11/2019		https://cordis.europa.eu/project/id/723059
enControl-Intuo	enControl-Intuo propose a connected home solution that helps reduce energy costs while preserving comfort for occupants.	30/06/2015		https://cordis.europa.eu/project/id/664165
EnerGAware	The main objective of the EnerGAware project is to achieve a 15-30% energy consumption and emissions reduction in a social housing pilot and increase the social tenants' understanding and engagement in energy efficiency.	30/04/2018		https://cordis.europa.eu/project/id/649673
ENTROPY	The ENTROPY aims at the integration between buildings and technologies that facilitate the deployment of innovative energy aware IT ecosystems for motivating end-users' behavioural changes	30/11/2018		https://cordis.europa.eu/project/id/649849

e-SAFE	e-SAFE defines and develops a market-ready deep renovation system for non-historic buildings.	30/09/2024	■■■■	https://cordis.europa.eu/project/id/893135
eTEACHER	eTEACHER concept consists of encouraging and enabling energy behaviour change of building users by means of continuous interventions displayed through a set of empower tools to drive informed decisions in order to save energy and optimise indoor environment quality.	30/06/2021		https://cordis.europa.eu/project/id/768738
FEEdBACk	The objectives of the FEEdBACk project are to develop, integrate and trial a wide range of energy focused ICT and behaviour modification applications, that will be used to engage energy users and permit them to understand and change their energy consumption related behaviour.	30/04/2021		https://cordis.europa.eu/project/id/768935
FLEXCoop	FLEXCoop introduces an end-to-end Automated Demand Response Optimization Framework.	31/01/2021		https://cordis.europa.eu/project/id/773909
FORTESIE	The overall vision of FORTESIE is to design, demonstrate, validate and replicate innovative renovation packages in the building industry with Smart Performance-Based guarantees and financing, aiming at Efficient, Sustainable and Inclusive Energy (ESIE) use.	31/08/2025	■■■■■■■■	https://cordis.europa.eu/project/id/101080029

GAIA	This project aims to promote positive behavioural changes within school communities regarding energy consumption and sustainability awareness.	31/05/2019		https://cordis.europa.eu/project/id/696029
GeoFit	GEOFIT is an integrated industrially driven action aimed at deployment of cost effective enhanced geothermal systems (EGS) on energy efficient building retrofitting.	31/10/2022		https://cordis.europa.eu/project/id/792210
GREENSOUL	GreenSoul pursues higher energy efficiency in public buildings by altering the way people use energy consuming shared devices (lights, printers) and personal devices (personal pluggable appliances).	31/10/2019		https://cordis.europa.eu/project/id/696129
HACKS	The objective of HACKS is to achieve market transformation for heating and cooling (HAC) appliances by motivating consumers to replace old and inefficient equipment with new energy efficient equipment.	28/02/2023		https://cordis.europa.eu/project/id/845231
HAPPEN	The project is aimed at stimulating the market uptake of deep retrofitting of buildings, with special regard to the Mediterranean area and to the residential built stock.	31/12/2021		https://cordis.europa.eu/project/id/785072
HEART	HEART is a multifunctional retrofit toolkit within which different subcomponents – ICT, BEMS, HVAC, BIPV and Envelope Technologies – cooperate synergistically to transform an existing building into a Smart Building.	31/07/2022		https://cordis.europa.eu/project/id/768921

HIQ-Home	HIQ-Home aims at introducing an on-demand cloud service that implements multi-criteria optimization and dynamic user profiling methods in order to optimize performance in any smart building and in particular connected into a smart city.	31/10/2015		https://cordis.europa.eu/project/id/674167
HIT2GAP	The HIT2GAP project will develop a new generation of building monitoring and control tools based on advanced data treatment techniques allowing new approaches to assess building energy performance data	31/08/2019		https://cordis.europa.eu/project/id/680708
iBECOME	iBECOME project will increase intelligence, decarbonisation and decentralisation of the energy system by transforming building and operation data into products that can be profitable in the innovative business framework.	30/11/2023	■	https://cordis.europa.eu/project/id/894617
InBetween	inBETWEEN goes beyond currently available ICT technologies used for inducing the end User behaviour change towards more energy efficient lifestyle.	31/10/2020		https://cordis.europa.eu/project/id/768776
IndoorSTIMULI	IndoorSTIMULI project aim to examine different window views, glazing properties, temperatures, and wall finishes and quantify their impacts on human responses.	31/08/2023		https://cordis.europa.eu/project/id/101031380
MOBISTYLE	The overall aim of MOBISTYLE is to raise consumer awareness and awareness of ownership by providing attractive tailor-made combined knowledge services on	30/06/2020		https://cordis.europa.eu/project/id/723032

	energy use, indoor environment, health and lifestyle, by ICT-based solutions.			
NERO	The project develops and demonstrates nearly Zero Energy Wood Buildings design process and procurement models with reduced cost for large-scale use in the northern climatic conditions.	28/02/2021		https://cordis.europa.eu/project/id/754177
OrbEEt	OrbEEt proposes an ICT-based framework to induce behaviour change toward energy efficiency by transforming energy measurements into personalized feedback delivered through engaging user interfaces.	28/02/2018		https://cordis.europa.eu/project/id/649753
P2Endure	P2Endure aims to provide scalable, adaptable and ready-to-implement prefabricated Plug-and-Play (PnP) systems for deep renovation of building envelopes and technical systems	28/02/2021		https://cordis.europa.eu/project/id/723391
PEAKapp	PEAKapp targets the development of an unprecedented ICT-to- Human ecosystem to trigger lasting energy savings through behavioural change and continuous engagement.	30/06/2019		https://cordis.europa.eu/project/id/695945
PLUG-N-HARVEST	The main strategic goal of the PLUG-N-HARVEST proposal is to design, develop, demonstrate and exploit a new modular, plug-n-play concept/product for Adaptable/Dynamic Building Envelopes	30/11/2022		https://cordis.europa.eu/project/id/768735

PRELUDE	PRELUDE will facilitate the transition to clean energy by combining innovative, smart, low-cost solutions into a proactive optimization service.	31/05/2024	■■■	https://cordis.europa.eu/project/id/958345
ReCO2ST	ReCO2ST applies an easy 3-step approach to building renovations, resulting in major savings and heightened standards of living, at a near-zero energy coefficient.	31/12/2021		https://cordis.europa.eu/project/id/768576
REnnovates	The Ren(n)ovates proposal focuses on the deployment and demonstration of an innovative systemic, 4-step holistic approach comprising state-of-the-art renovation with state-or-the-art smart ICT control.	31/08/2018		https://cordis.europa.eu/project/id/680603
RenoZEB	RenoZEB aims to unlock the nZEB renovation market leveraging the gain on property value through a new systemic approach to retrofitting that will include innovative components, processes and decision making methodologies.	31/01/2022		https://cordis.europa.eu/project/id/768718
REScoopVPP	The EU-funded REScoopVPP project will establish the most advanced community-driven smart building ecosystem for energy communities	30/11/2023	■	https://cordis.europa.eu/project/id/893240
RESPOND	RESPOND will aim to deploy and demonstrate an interoperable, cost effective, user centred solution, entailing energy automation, control and monitoring tools.	30/09/2020		https://cordis.europa.eu/project/id/768619

SAB	The EU-funded SAB project will support an integrated solution for air quality	29/02/2020		https://cordis.europa.eu/project/id/886446
SENSIBLE	The goal of this project is to develop novel information sensing research and innovation approaches for acquiring, communicating and processing a large volume of heterogeneous datasets in the context of smart buildings.	30/06/2022		https://cordis.europa.eu/project/id/734331
SHAPE	SHAPE aim to address association of health, wellbeing, smartness and indoor environmental quality (IEQ) with nearly zero energy buildings (nZEBs)	30/10/2023	■	https://cordis.europa.eu/project/id/101032267
SMART2B	SMART2B aims to upgrade smartness levels of existing buildings through coordinated control of legacy equipment and smart appliances, and implement interoperability in two existing cloud-based platforms that are currently available in the European market.	31/08/2024	■■■■	https://cordis.europa.eu/project/id/101023666
SMARTeeSTORY	SMARTeeSTORY will propose an integrated building automation and control systems for monitoring and optimizing building energy performance according to an innovative multi-domain approach.	30/04/2027	■■■■■■■■■■■■■■■	https://cordis.europa.eu/project/id/101103956
SocialWatt	SocialWatt aims to support obligated parties under Article 7 of the Energy Efficiency Directive to develop, adopt, test and spread innovative energy poverty schemes across Europe	31/03/2023		https://cordis.europa.eu

				/project/id/845905
STEP-IN	STEP-IN will develop a global methodology for the effective analysis and tackling of energy poverty	31/03/2021		https://cordis.europa.eu/project/id/785125
StepUP	The EU-funded StepUP project will develop a new deep renovation methodology, based on understanding both building performance and impact of the interventions through building data and physics-based modelling.	30/04/2024	■■■	https://cordis.europa.eu/project/id/847053
Surefit	Surefit will demonstrate fast-track renovation of existing domestic buildings by integrating innovative, cost-effective, and environmentally conscious prefabricated technologies	28/02/2025	■■■■■■	https://cordis.europa.eu/project/id/894511
TABEDE	TABEDE aims to allow all buildings equipped with Building Energy Management Systems to integrate energy grid demand response schemes, overcoming limitations linked to missing interoperability.	30/04/2021		https://cordis.europa.eu/project/id/766733
TRIBE	TRIBE project aims to contribute to a citizens' behaviour change towards energy efficiency in public buildings, through their engagement in the experience of playing a social game, linked by ICT to real time data collected.	28/02/2018		https://cordis.europa.eu/project/id/649770
TripleA-reno	The overall aim of TripleA-reno is to make acceptation and decision making on deep and nZE renovation attractive for	31/10/2021		https://cordis.europa.eu

	consumers and end-users through clear and meaningful information and communication on proven performances on energy, Indoor Environmental Quality and personal health.			/project/id/784972
TURNKEY RETROFIT	TURNKEY RETROFIT project aims at developing and replicating an integrated home renovation service that will transform the complex and fragmented renovation process into a simple, straightforward and attractive process for the homeowner.	28/02/2022		https://cordis.europa.eu/project/id/839134
TwinERGY	TwinERGY will introduce a first-of-a-kind Digital Twin framework that will incorporate the required intelligence for optimizing demand response at the local level without compromising the well-being of consumers and their daily schedules and operations.	31/10/2023	■	https://cordis.europa.eu/project/id/957736
U-CERT	The main aim of U-CERT is to introduce a next generation of user centred certification schemes to value buildings in a holistic and cost-effective manner	28/02/2023		https://cordis.europa.eu/project/id/839937
UtilitEE	UtilitEE project focuses on discovering, quantifying and revealing energy-hungry activities and conveys meaningful feedback to engage users into a continuous process of learning and improvement	30/04/2021		https://cordis.europa.eu/project/id/768600
Yodiwo FEMP	Yodiwo FEMP project is an IoT-based platform that intends to perfect facility management systems and increase the energy efficiency of commercial buildings.	31/03/2020		https://cordis.europa.eu

				/project/id/886906
ZERO-PLUS	In ZERO-PLUS, a comprehensive, cost-effective system for Net Zero Energy (NZE) settlements will be developed and implemented.	31/12/2020		https://cordis.europa.eu/project/id/678407
EBENTO	EBENTO will develop a one-stop-shop platform for all actors involved in building and renovation sector to better manage Energy Performance Contracting	30/09/2025	■■■■■■■■■	https://cordis.europa.eu/project/id/101079888
ePANACEA	ePANACEA project aims to create a holistic methodology for energy performance assessment and certification of buildings that can include smart and novel technologies and users' perspective	31/10/2023	■	https://cordis.europa.eu/project/id/892421
Homes4Life	Homes4Life project will define a certification scheme for age-friendly homes based on a user-centric approach.	28/02/2021		https://cordis.europa.eu/project/id/826295
InterConnect	InterConnect envisages to contribute for the democratization of efficient energy management, through a flexible and interoperable ecosystem where demand side flexibility can be soundly integrated with effective benefits to end-users.	31/03/2024	■■■	https://cordis.europa.eu/project/id/857237
MODERATE	MODERATE enables uniform access to heterogeneous data sources on buildings' performance, usually dispersed in non-	31/05/2026	■■■■■■■■■■■■■	https://cordis.europa.eu

	interoperable data silos. It develops techniques to enable building owners, policy makers, facility managers, utility companies (etc.) to openly share their data, gain insights, and make decisions compliant with regulations.			/project/id/101069834
MORE-CONNECT	Objective is to develop and to demonstrate technologies and components for prefabricated modular renovation elements in Europe	31/05/2019		https://cordis.europa.eu/project/id/633477
PHOENIX	PHOENIX will design the necessary hardware and software upgrades and make use of artificial intelligence technologies as well as edge/cloud computing methods to transform existing buildings into smart buildings	31/08/2023		https://cordis.europa.eu/project/id/893079
PRECEPT	PRECEPT ambitiously aims to set the grounds for the deployment and operation of proactive residential buildings	31/03/2024	■■■	https://cordis.europa.eu/project/id/958284
SATO	The SATO project implements a cloud-based platform to perform self-assessment and optimization of buildings' energy and energy-consuming devices	30/09/2024	■■■■■	https://cordis.europa.eu/project/id/957128
SIRENE	The main aim of the SIRENE proposal is to support the growth of social innovation ecosystems delivering eco-friendly and sustainable community-based services for Smart Healthy Age-Friendly Environments	31/10/2024	■■■■■	https://cordis.europa.eu/project/id/101096077

From [269]*:*

ACCEPT	ACCEPT project aim to develop and deliver a digital toolbox, that allows energy communities to offer innovative digital services to reduce the dependency on fossil fuels, save energy in the users households without compromising the quality of living	30/06/2024	■■■■	https://cordis.europa.eu/project/id/957781
Auto-DAN	Auto-DAN exploit the evolution of IoT and emerging technologies to capture data and create solutions that will enable the self-optimisation of the building's energy consumption.	30/09/2024	■■■■■	https://cordis.europa.eu/project/id/101000169
Cultural-E	Cultural-E project define modular and replicable solutions for Plus Energy Buildings (PEBs), accounting for climate and cultural differences, while engaging all key players involved in the building life cycle	30/09/2024	■■■■■	https://cordis.europa.eu/project/id/870072
EBENTO	EBENTO will develop a one-stop-shop platform for all actors involved in building and renovation sector to better manage Energy Performance Contracting	30/09/2025	■■■■■■■■■	https://cordis.europa.eu/project/id/101079888
ePANACEA	ePANACEA project aims to create a holistic methodology for energy performance assessment and certification of buildings that can include smart and novel technologies and users' perspective	31/10/2023	■	https://cordis.europa.eu/project/id/892421
Homes4Life	Homes4Life project will define a certification scheme for age-friendly homes based on a user-centric approach.	28/02/2021		https://cordis.europa.eu

				/project/id/ 826295
InterConnect	InterConnect envisages to contribute for the democratization of efficient energy management, through a flexible and interoperable ecosystem where demand side flexibility can be soundly integrated with effective benefits to end-users.	31/03/2024	■■■	https://cordis.europa.eu /project/id/ 857237
MODERATE	MODERATE enables uniform access to heterogeneous data sources on buildings' performance, usually dispersed in non-interoperable data silos. It develops techniques to enable building owners, policy makers, facility managers, utility companies (etc.) to openly share their data, gain insights, and make decisions compliant with regulations.	31/05/2026	■■■■■■■■■■■■■	https://cordis.europa.eu /project/id/ 101069834
MORE-CONNECT	Objective is to develop and to demonstrate technologies and components for prefabricated modular renovation elements in Europe	31/05/2019		https://cordis.europa.eu /project/id/ 633477
PHOENIX	PHOENIX will design the necessary hardware and software upgrades and make use of artificial intelligence technologies as well as edge/cloud computing methods to transform existing buildings into smart buildings	31/08/2023		https://cordis.europa.eu /project/id/ 893079

APPENDIX C

Integrating Cozie into MOQA (Home Assistant)

Home Assistant 2023.2.5
Supervisor 2023.12.0
Operating System 10.1
Frontend 20230503.1 – latest

1. Install AppDeamon on Home Assistant
    - 1.1. From the Add-on menu (Settings->Add-ons->Add-on Store) install AppDeamon.
    - 1.2 In the AppDeamon dashboard, go to the Configuration tab. Under “python packages”, add “pandas” and “openpyxl”
    - 1.3. Run AppDeamon from the Info tab.
2. Configure an App to obtain, for example, the number of micro-surveys submitted through Cozie. Any information contained in the dataframe that Cozie creates automatically can be translated into home assistant entities.
    - 2.1 Go to /homeassistant/appdaemon/apps/ and create “cozie_data.py” file (this can be done using the File Editor add-on, for example)
    - 2.2. To create an entity that stores the number of micro-surveys submitted, configure “cozie_data.py” file as follows:

```
import appdaemon.plugins.hass.hassapi as hass
import requests
import pandas as pd
from io import BytesIO
import zipfile

class CozieData(hass.Hass):
    def initialize(self):
        # Immediate call to update the sensor at the time of app loading
        self.update_sensor(None)
        # Execute your logic here or use a time handle to schedule the
execution
        self.run_daily(self.update_sensor, "00:00:00")
    def update_sensor(self, kwargs):
        # Code to download and process data
        import requests
        import json
```

```
        import pandas as pd
        import shutil
        # Settings
        YOUR_TIMEZONE = 'Europe/Rome'
        ID_PARTICIPANT = ['351_A']
        ID_EXPERIMENT = 'Measure'
        WEEKS = "20"  # Number of weeks from which the data is retrived,
starting from now
        API_KEY = ****API_KEY**** # reach out to cozie.app@gmail.com for
an API_KEY
        # Query data
        payload  =  {'id_participant':  ID_PARTICIPANT,'id_experiment':
ID_EXPERIMENT, 'weeks': WEEKS}
        headers = {"Accept": "application/json", 'x-api-key': API_KEY}
        response   =   requests.get('https://m7cy76lxmi.execute-api.ap-
southeast-1.amazonaws.com/default/cozie-apple-researcher-read-influx',
params=payload, headers=headers)
        url = response.content
        # Download zipped CSV file with Cozie data
        with requests.get(url, stream=True) as r:
            with open('cozie.zip', 'wb') as f:
                shutil.copyfileobj(r.raw, f)
        # Convert zipped CSV file with Cozie to dataframe
        with open('cozie.zip', 'rb') as f:
              df   =   pd.read_csv(f,   compression={'method':   'zip',
'archive_name': 'sample.csv'})
        df = df.drop(columns=['Unnamed: 0'])
        df['index'] = pd.to_datetime(df['index'])
        df = df.set_index('index')
        df.index = df.index.tz_convert(YOUR_TIMEZONE)
        # Get only question flow responses
        df_questions = df[df["ws_survey_count"].notna()]
        #delete empty columns
        df_questions = df_questions.dropna(axis=1, how='all')
        # Let's assume that questions_length is the calculated length:
        questions_length = len(df_questions)
        # Update or create a sensor in Home Assistant
        self.set_state("sensor.cozie_questions_count",
state=questions_length)
```

2.3 Go to /homeassistant/appdaemon/apps/apps.yaml and add the script you have created:

```
cozie_data:
  module: cozie_data
  class: CozieData
```

3. Restart Home Assistant. The number of votes submitted in the period defined by the variable 'WEEKS' will be stored in “sensor.cozie_questions_count”

Integrating the constantly updated value of electricity price from ARERA into MOQA (Home Assistant)

Home Assistant 2023.2.5
Supervisor 2023.12.0
Operating System 10.1
Frontend 20230503.1 – latest

1. Install AppDeamon on Home Assistant
    1.1. From the Add-on menu (Settings->Add-ons->Add-on Store) install AppDeamon.
    1.2 In the AppDeamon dashboard, go to the Configuration tab. Under “python packages”, add “pandas” and “openpyxl”
    1.3. Run AppDeamon from the Info tab.
2. Configure the App
    2.1 Navigate to /homeassistant/appdaemon/apps/ and create “electricity.py” file (this can be done using the File Editor add-on, for example)
    2.2. Configure the “electricity.py” file as follows:

```
import pandas as pd
import appdaemon.plugins.hass.hassapi as hass

class ReadExcel(hass.Hass):
    def initialize(self):
        self.log("Electricity price import script started")
        #self.run_in(self.update, 0)
      # We only need to update every 60mins really.
        self.run_every(self.update, "now", 60*60)
    # read by default 1st sheet of an excel file
    def update(self, kwargs):
        dataframe1=
pd.read_excel('https://www.arera.it/allegati/dati/ele/eep35new.xlsx')
        #self.log(dataframe1)
        df2=dataframe1.dropna()
        #self.log(df2)
        elec_price = round(df2.iloc[-1,-1]/100,3)
        self.log(elec_price)
        entity = "sensor.electricity_price"
        self.set_state(entity, state = elec_price)
```

2.3 Go to /homeassistant/appdaemon/apps/apps.yaml and add the script you have created:

```
sensor_excel:
  module: electricity
  class: ReadExcel
```

3. Restart Home Assistant. Values will be stored in “sensor.electricity_price” and updated every 60 minutes.

APPENDIX D

The graphic design of the dashboard is based on the UI-Lovelace-Minimalist theme created by tben (https://ui-lovelace-minimalist.github.io/UI/). It is recommended to refer to the page for the initial setup.

Below is the file organization in version 3 of the dashboard, presented in Section 5.2.5, along with a brief explanation.

```
config\
        …
        appdaemon\
                apps\
                        electricity.py
                        cozie_data.py
        …
        ui_lovelace_minimalist\
                dashboard\
                        adaptive-dash\
                                adaptive-ui.yaml
                        views\
                                cards\
                                        temp.yaml
                                        hum.yaml
                                        …
                                main.yaml
                                main2.yaml
                                main3.yaml
                                redirect_1.yaml
                                redirect_2.yaml
        sensors.yaml
        configuration.yaml
        automations.yaml
```

`electricity.py`: Python script that queries the ARERA website every 60 minutes (the value can be changed if desired) to obtain electricity price averages in Italy and updates the entity status accordingly (see Appendix C).

`cozie_data.py`: Python script that queries via API the Cozie server to obtain feedback data reported in micro-surveys conducted via smartwatch (see Appendix C).

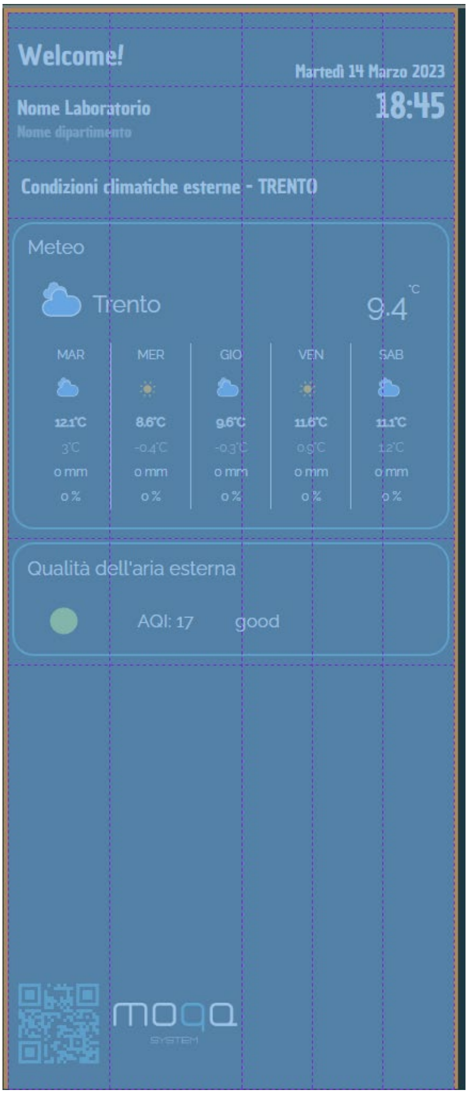
`adpative-ui.yaml:` Basic YAML that contains the 'first' grid division of the main view. One-third is dedicated to the 'main.yaml' column (which presents general information and external weather data), and two-thirds to 'main2.yaml' (for the 'indoor environmental quality' view) or 'main3.yaml' (for the 'energy consumption' view). It also includes references to the 'redirect_1.yaml' and 'redirect_2.yaml' files:

```
---
button_card_templates:                                   !include_dir_merge_named
"../../../custom_components/ui_lovelace_minimalist/__ui_minimalist__/ulm_templat
es/"

title: "UI Lovelace Minimalist"
theme: "minimalist-desktop-dark"
#background: "var(--background-image)"
background: "#1c3842"
views:
  - type: "custom:grid-layout"
    title: "Qualità ambientale interna"
    # icon: "mdi:home"
    path: "0"

    layout:
      grid-template-columns: "1fr 2fr"
      margin: 0px
      padding-top: 100px
      grid-template-rows: "calc(100vh - 60px)"
      grid-template-areas: |
        "main main2"
      # mediaquery:
      #   "(max-width: 1100px), (orientation: portrait)":
      #     grid-template-columns: "100%"
      #     grid-template-areas: "main"
    cards:
      - !include "views/main.yaml"
      - !include "views/main2.yaml"
      - !include "views/redirect_1.yaml"

  - type: "custom:grid-layout"
    title: "Consumi"
    #icon: "mdi:sofa"
    path: "consumi"
    layout:
      grid-template-columns: "1fr 2fr"
      margin: 0px
      padding-top: 100px
      grid-template-rows: "calc(100vh - 60px)"
      grid-template-areas: |
```

```
  "main main3"
 # mediaquery:
 #  "(max-width: 1100px), (orientation: portrait)":
 #   grid-template-columns: "100%"
 #   grid-template-areas: "livingroom"
cards:
 - !include "views/main.yaml"
 - !include "views/main3.yaml"
 - !include "views/redirect_2.yaml"
```

`main.yaml`: Left column configuration YAML. The content organization grid (image on the right) is organized as follows:

". . . . . ."
"text text text time time time"
"location location location time time time"
"title1 title1 title1 title1 title1 title1"
"weather weather weather weather weather weather"
"title2 title2 title2 title2 title2 title2"
"card4 card5 . . . ."
where the dots indicate empty cells.



MAR	MER	GIO	VEN	SAB
12.1°C	8.6°C	9.6°C	11.6°C	11.1°C
3°C	-0.4°C	-0.3°C	0.9°C	1.2°C
0 mm	0 mm	0 mm	0 mm	0 mm
0 %	0 %	0 %	0 %	0 %

For example, the content "time" is present both in the second and third rows, from the third to the sixth column (image on the right).
Each remaining content occupies a row. Each content, or "block", consists of modified "custom button cards". The custom button cards can be downloaded through the HACS add-on (https://hacs.xyz/).
Some blocks, like "Outdoor air quality" ("Qualità aria esterna"), are grids themselves. In this case, the block has two rows and two columns: "titlequal titlequal" and "sensor state". The first row is entirely occupied by the title, in the second row the first column displays the sensor value, the second column shows the state ("good"):

```
[…]
########### TAB AIR QUALITY ######################
- view_layout:
    grid-area: "title2"
  type: custom:mod-card
  card_mod:
      style: |
          ha-card {
              border-color: #4192a8;
              border-style: solid;
              border-width: 0.2vw;
              #padding: 2%;
          }
  card:
    type: "custom:layout-card"
    layout_type: "custom:grid-layout"
    background-color: "#1c3842"
    layout:
      grid-template-columns: "1fr 1fr"
      grid-template-rows: "min-content min-content"
      grid-template-areas: |
        "titlequal titlequal"
        "sensor state"
    cards:
      - view_layout:
          grid-area: "titlequal"
        type: "custom:button-card"
        #template: "card_title"
        name: "Outdoor Air Quality"
        styles:
          card:
            - background-color: "rgba(0,0,0,0)"
            - box-shadow: "none"
            - border-radius: 0%
            - padding: 1%
          name:
            - font-size: 1.25vw
            - justify-self: left
        tap_action:
          action: none
      - view_layout:
          grid-area: "sensor"
        style: |
          :host {
            align-self: center
          }
        type: 'custom:button-card'
        entity: sensor.ext_air_quality_index
        #template: no_background
        name: AQI
```

```
        show_state: true
        show_icon: true
        show_name: true
        icon: mdi:circle
        layout: icon_name_state
        styles:
          icon:
            - color: >
                [[[
                  if (entity.state <= 50) return '#a9d04c';
                  if (entity.state > 50 && entity.state <= 100) return '#fcdc2a';
                  if (entity.state > 100 && entity.state <= 150) return '#f79229';
                  if (entity.state > 150 && entity.state <= 200) return '#ee3331';
                  if (entity.state > 200 && entity.state <= 300) return '#9803fc';
                  else return '#2e0207';
                ]]]
          card:
            - background-color: "rgba(0,0,0,0)"
            - font-size: 1.2vw
            - box-shadow: "none"
            - border-radius: 0%
          name:
            #- justify-self: left
      - view_layout:
          grid-area: "state"
        style: |
          :host {
            align-self: center
          }
        type: 'custom:button-card'
        entity: sensor.ext_air_pollution_level
        #template: no_background
        show_state: true
        show_icon: false
        show_name: false
        styles:
          grid:
            - grid-template-areas: '"s"'
            - grid-template-rows: min-content
            - grid-template-columns: 1fr
          card:
            - background-color: "rgba(0,0,0,0)"
            #- font-family: Chau Philomene One;
            - box-shadow: "none"
            - border-radius: 0%
            - font-size: 1.2vw
          state:
            - justify-self: left"
```

[…]

`main2.yaml:` Configuration YAML for the right side of the 'environmental quality' view. As there are numerous 'blocks' (cards) to be inserted, a YAML file is created for each card (temperature, humidity, title1, text, table...), which is not done for the main.yaml file, where everything is contained within it (the code of the air quality tab presented above is only a part of it). In main2.yaml, only the grid and its dimensions are specified, the cards that will take place in the grid are in separate files and are called within the file:

```
    - !include "cards/title1.yaml"
    - !include "cards/title2.yaml"
    - !include "cards/temp.yaml"
    - !include "cards/hum.yaml"
    - !include "cards/co2.yaml"
    - !include "cards/pm25.yaml"
    - !include "cards/tvoc.yaml"
    - !include "cards/radon.yaml"
    - !include "cards/qualita.yaml"
    - !include "cards/tab.yaml"
```

The grid has the following structure:

"title1 title1 title1 title1 title1 title1 title1 title1"
"temp temp temp . hum hum hum ."
"title2 title2 title2 title2 title2 title2 title2 title2"
"co2 co2 co2 . pm25 pm25 pm25 ."
"tvoc tvoc tvoc . radon radon radon ."
". . . . ."
"qualita qualita qualita . tab tab tab ."

As before, the dots are empty cells, used as 'spacing'. For space reasons, the extended code is not reported.

`temp.yaml: A`s an example, here’s the code of the block containing the indoor temperature information.

```
########### TEMPERATURE VALUE ######################
view_layout:
  grid-area: "temp"
type: vertical-stack
cards:
  - type: 'custom:mini-graph-card'
    entities:
      - sensor.028_airthings_temperature
    show:
      labels: hover
      icon_adaptive_color: true
```

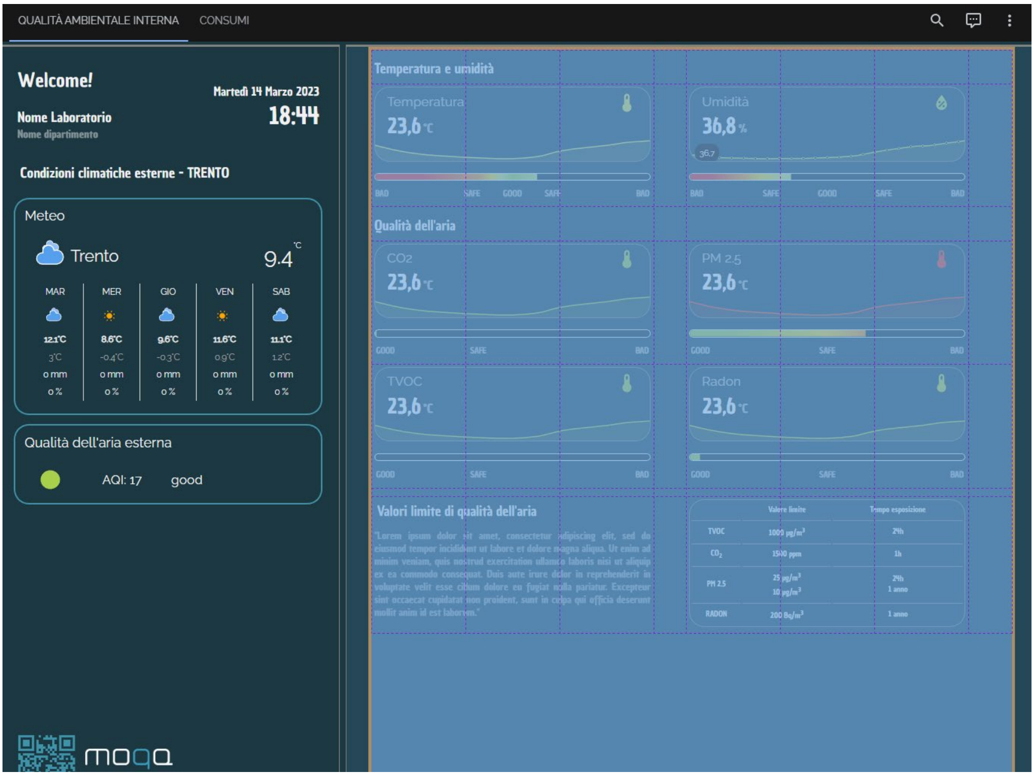
```
  #name_adaptive_color: true
color_thresholds_transition: smooth #hard
# color_thresholds:
#   - value: 0
#     color: "#FF0000"
#   - value: 18.5
#     color: '#3A9AB8'
#   - value: 26
#     color: "#FF0000"
color_thresholds:
  - value: 0
    color: "#ee3331"
  - value: 14
    color: "#f79229"
  - value: 16
    color: "#fcdc2a"
  - value: 18
    color: "#d0e17c"
  - value: 19
    color: "#a9d04c"
  - value: 21
    color: "#d0e17c"
  - value: 27
    color: "#fcdc2a"
  - value: 29
    color: "#f79229"
  - value: 32
    color: "#ee3331"
line_width: 2
name: Temperatura
hours_to_show: 24
hour24: true
points_per_hour: 1
height: 40
card_mod:
    style: |
      :host {
        --mdc-icon-size: 2vw;
      }
      .name {
        font-size: 1vw ;
        self-align: center;
      }
      .header {
        padding-bottom: 0px;
      }
      .states {
        padding-bottom: 0px;
      }
```

```
          ha-card {
            padding-top: 0.4vw !important;
            --primary-text-color: white;
            --ha-card-background: rgba(0,0,0,0);

            border-color: #81827e;
            border-width: 0.1vw;
            border-style: solid;
          }
          ha-card > div.states.flex > div.state.false {
            font-family: Chau Philomene One;
            font-size: 0.8vw;

          .name > span{
            /*font-size: 1vw !important;*/
            max-height: none !important;
          }
          .ellipsis{
            overflow: none;
          }
  ################## LEGEND (GRADIENT)  ###########################
  - type: custom:bar-card
    entities:
      - entity: sensor.028_airthings_temperature
    max: 40
    min: 0
    height: 0.6vw
    entity_row: true
    positions:
      indicator: off
      icon: off
      value: off
      name: off
    style: |-
      bar-card-currentbar, bar-card-backgroundbar  {
        /*border-radius: 12px;*/
        background: linear-gradient(to right,
          #ee3331 17.5%,
          #f79229 37.5%,
          #fcdc2a 42.5%,
          #d0e17c 46.25%,
          #a9d04c 50%,
          #d0e17c 60%,
          #fcdc2a 70%,
          #f79229 76.25%,
          #ee3331 90% );
        clip-path: polygon(0 0, var(--bar-percent) 0, var(--bar-percent) 100%, 0
100%);
      }
      bar-card-backgroundbar  {
```

```
      background: black;
    }
    bar-card-background {
      margin: 0px !important;
    }
    bar-card-card{
      border-style: solid;
      border-radius: 12px;
      border-width: 0.1vw
    }
    ha-card{
      padding-top: 0.5vw;
    }
################## LEGEND LABELS ###########################
- type: horizontal-stack
  cards:
    - type: "custom:button-card"
      name: "BAD"
      styles:
        card:
          - background-color: "rgba(0,0,0,0)"
          - box-shadow: "none"
          - border-radius: 0%
          - padding: 2%
          - font-family: Chau Philomene One
          - opacity: 0.65
        name:
          - font-size: 0.75vw

          - justify-self: left
      tap_action:
        action: none
    - type: "custom:button-card"

      name: "SAFE"
      styles:
        card:
          - background-color: "rgba(0,0,0,0)"
          - box-shadow: "none"
          - border-radius: 0%
          - padding: 2%
          - font-family: Chau Philomene One
          - opacity: 0.65
        name:
          - font-size: 0.75vw

          - justify-self: right
      tap_action:
        action: none
```

```
- type: "custom:button-card"
  #template: "card_title"
  name: "GOOD"
  styles:
    card:
      - background-color: "rgba(0,0,0,0)"
      - box-shadow: "none"
      - border-radius: 0%
      - padding: 2%
      - font-family: Chau Philomene One
      - opacity: 0.65
    name:
      - font-size: 0.75vw

      - justify-self: center
  tap_action:
    action: none
- type: "custom:button-card"
  #template: "card_title"
  name: "SAFE"
  styles:
    card:
      - background-color: "rgba(0,0,0,0)"
      - box-shadow: "none"
      - border-radius: 0%
      - padding: 2%
      - font-family: Chau Philomene One
      - opacity: 0.65
    name:
      - font-size: 0.75vw
      - justify-self: left
  tap_action:
    action: none
- type: "custom:button-card"
  #template: "card_title"
  name: "BAD"
  styles:
    card:
      - background-color: "rgba(0,0,0,0)"
      - box-shadow: "none"
      - border-radius: 0%
      - padding: 2%
      - font-family: Chau Philomene One
      - opacity: 0.65
    name:
      - font-size: 0.75vw
      - justify-self: right
  tap_action:
    action: none
```

The result is:



Valori limite di qualità dell'aria

"Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum."

	Valore limite	Tempo esposizione
TVOC	1000 µg/m^3	24h
CO$_2$	1500 ppm	1h
PM 2.5	25 µg/m^3 10 µg/m^3	24h 1 anno
RADON	200 Bq/m^3	1 anno

`main3.yaml`: Configuration YAML for the right side of the 'energy simulation' view. The structure is similar to main2.yaml.

"Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat."

"Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore"

In this view, customized buttons have been added, allowing the selection of monitored electrical devices one by one or in groups. For space reasons, the extended code is not reported.

`redirect_1` and **`redirect_2`**: To enable mouse and keyboard-free access to the interface, an automation based on a timer (the entity “timer.timer1”) has been developed, which updates the views 'Indoor environmental quality' and 'Energy consumption' every 30 seconds. The file redirect_1.yaml serves to return the view to the IEQ page, the file redirect_1.yaml serves to return the view to the consumption page. Here is the code for redirect_1.yaml:

```
type: 'custom:tab-redirect-card'
redirect:
- user: 'Visualizza'
  entity_id: 'timer.timer1'
  entity_state: 'idle'
  redirect_to_tab_index: 1
```

The time entity is defined in sensor.yaml:

```
timer:
  timer1:
    duration: "00:00:30"
```

`configuration.yaml`, **`sensor.yaml`**, and **`automation.yaml`**: contain all the additional entities needed for operation (timer, input_boolean, sensors, binary_sensor, etc.). For space reasons, the extended code is not reported.

APPENDIX E

Interview Set 1: Pre-Installation and First Year Without Data Access

1. How do you manage the relationship between the comfort you feel in your home, like the right temperature and fresh air, and the amount of energy used to achieve this comfort?

2. What does energy saving mean to you? What practices do you typically implement to save energy, and how do you decide between different options?

3. Before having the MOQA system installed, how did you manage and track your household's energy usage and environmental conditions? Were there any specific challenges or concerns you hoped this system would address?

4. What were your initial thoughts and feelings about introducing a monitoring system into your private space? Did you have any privacy concerns, and how did you reconcile with them?

5. How did you perceive the presence of the sensors in your home? Did it influence your behavior or awareness regarding energy consumption and environmental impact? Were there any moments when you wished you had access to the environmental and energy data?

6. How did you feel about the potential for this technology to impact your daily life? Did you have any concerns or expectations about the insights you would eventually receive?

7. Without the immediate feedback from the system, did you find yourself changing any habits or making any home improvements in anticipation of eventually being able to measure their impact?

Interview Set 2: Post-Installation with Data Access

1. After gaining access to the data collected by the Home Assistant system, how has your understanding of your home's energy and environmental conditions changed? Can you provide specific examples?

2. Describe how the availability of data has influenced your daily routines or lifestyle. Have you implemented any changes based on the insights provided?

3. Having had a year to reflect, have your initial privacy concerns been addressed? How do you now view the trade-off between personal privacy and the benefits of environmental and energy monitoring?

4. What specific features or data points have you found most useful or enlightening, and why? Are there any metrics you pay more attention to?

5. Can you share any concerns regarding data privacy or security that arose after you started receiving the data? How have you addressed these concerns, if at all?

6. With the insights gained from the monitoring data, what additional capabilities or improvements would you like to see integrated into the system?

7. Would you say that the system has met, exceeded, or failed to meet your original expectations now that you have had time to analyze the data? What has been the most surprising aspect of having this technology in your home?

APPENDIX F

Sending text messages from Telegram to MOQA (Home Assistant): indoor comfort occupant feedback

Home Assistant 2023.2.5
Supervisor 2023.11.6
Operating System 9.5
Frontend 20230202.0 – latest

1. Create a Telegram Bot:

    1.1. Go to Telegram on your smartphone and search for the "@BotFather" bot. Initiate a chat with BotFather and follow the instructions to create a new bot. You will receive an access token that we will use later (=TOKEN_BOT).

    1.2. Send any message to the chat bot you have created.

    Go to https://api.telegram.org/botTOKEN_BOT/getUpdates. You will get something like:

```
{
   "ok":true,
   "result":[
      {
         "update_id":418921702,
         "message":{
            "message_id":6,
            "from":{
               "id":"CHAT_ID",
               "is_bot":false,
               "first_name":"Nicola",
               "username":"Nicola",
               "language_code":"it"
            },
            "chat":{
               "id":"CHAT_ID",
               "first_name":"Nicola",
               "username":"Nicola",
               "type":"private"
            },
            "date":2342423,
            "text":"ciao"
         }
      }
   ]
```

```
}
```

Annotate CHAT_ID

2. Configure Home Assistant:
    2.1. Make sure Home Assistant is installed and working.
    2.2. Add the "Telegram Bot" component to the Home Assistant configuration. You can do this by adding the following lines to your configuration.yaml file:

```
telegram_bot:
  - platform: polling
    api_key: TOKEN_BOT
    allowed_chat_ids:
      - CHAT_ID
notify:
  - name: telegram_notifier
    platform: telegram
    chat_id: CHAT_ID
```

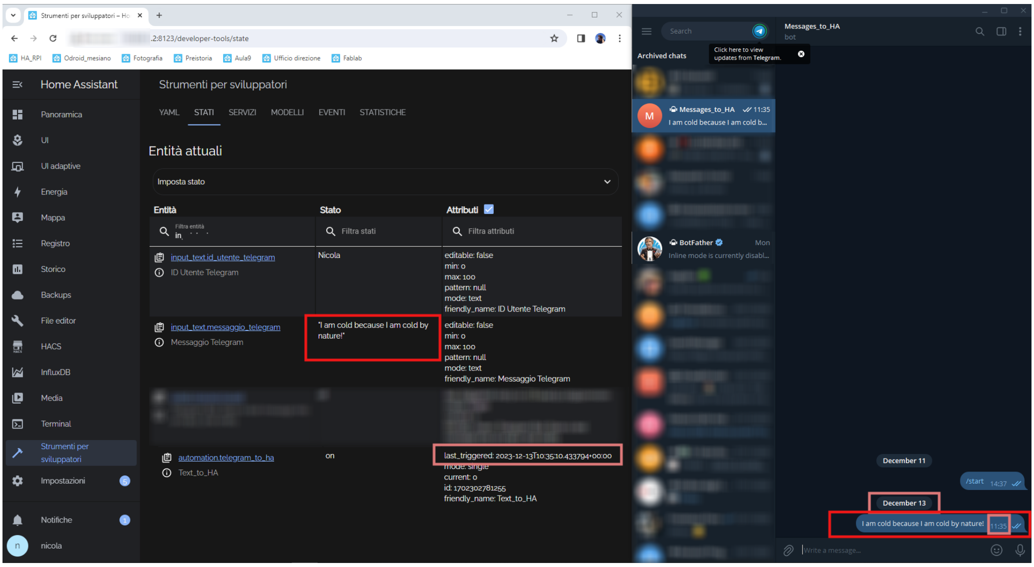
2.3. To store the text message in a variable in Home Assistant, you can use the input_text component. Add the following configuration to the configuration.yaml file:

```
input_text:
  messaggio_telegram:
    name: Messaggio Telegram
  id_utente_telegram:
    name: ID Utente Telegram
```

2.4. Create an automation that receives messages from Telegram and stores the text in the input_text.messaggio_telegram variable. Add this to your automations.yaml file:

```
- id: '1702302781255' #### set as desired
  alias: Text_to_HA   #### set as desired
  description: Save telegram text message in input_text
  trigger:
  - platform: event
    event_type: telegram_text
  condition: []
  action:
    - service: input_text.set_value
      target:
        entity_id: input_text.messaggio_telegram
      data:
        value: >-
          "{{ trigger.event.data.text}}"
    - service: input_text.set_value
      target:
        entity_id: input_text.id_utente_telegram
      data:
        value: "{{ trigger.event.data.from_first }}"
  mode: single
```

3. Verify proper functioning



Entità	Stato	Attributi
input_text.id_utente_telegram ID Utente Telegram	Nicola	editable: false min: 0 max: 100 pattern: null mode: text friendly_name: ID Utente Telegram
input_text.messaggio_telegram Messaggio Telegram	"I am cold because I am cold by nature!"	editable: false min: 0 max: 100 pattern: null mode: text friendly_name: Messaggio Telegram
[redacted]	[redacted]	[redacted]
automation.telegram_to_ha Text_to_HA	on	last_triggered: 2023-12-13T10:35:10.433794+00:00 mode: single current: 0 id: 1702302781255 friendly_name: Text_to_HA

Messages_to_HA 11:35

December 11

/start 14:37

December 13

I am cold because I am cold by nature! 11:35

Sending alerts from MOQA (Home Assistant) to Telegram: unavailable entities notification

Home Assistant 2023.2.5

Supervisor 2023.11.6

Operating System 9.5

Frontend 20230202.0 – latest

1. Create a new Telegram bot and configure Home Assistant for it as illustrated before. In configuration.yaml:

```
telegram_bot:
  - platform: polling
    api_key: TOKEN_BOT2
    allowed_chat_ids:
      - CHAT_ID2
notify:
  - name: telegram_bot
    platform: telegram
    chat_id: CHAT_ID2
```

2. Configure the blueprint project

2.1. From the blueprint menu (Settings->Automations & scenes->Blueprints) import to HA the blueprint project available at: https://github.com/gmlupatelli/blueprints_repo/blob/e3945ad01d9eddc2fda920 d6cec5c5c9ccf19f8e/unavailable_entities_notification/unavailable_entities_notification.yaml

(see blueprints_repo/LICENSE at e3945ad01d9eddc2fda920d6cec5c5c9ccf19f8e · gmlupatelli/blueprints_repo · GitHub for license)

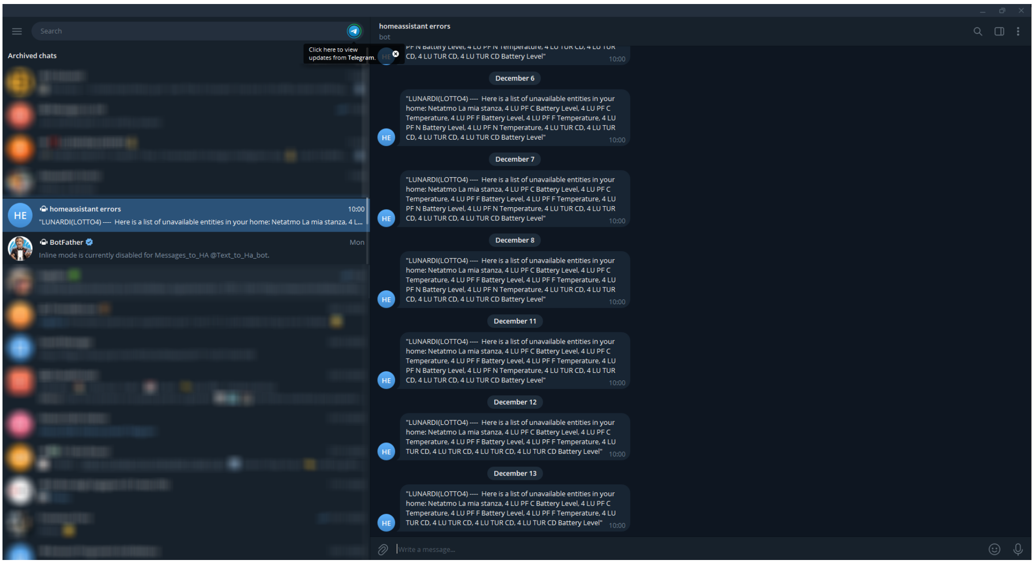
2.2. From the blueprint menu (Settings->Automations & scenes->Blueprints) click on the "create automation" button located next to the blueprint you just imported.

Set the notification interval as desired through the GUI.

Add the following code as action:

```
service: notify.telegram_bot
data:
  message: >-
    "****MY_HOUSE_NAME**** ----  Here is a list of unavailable entities in your home: {{ entities|replace('_', ' ') }}"
```

3. Verify proper functioning



homeassistant errors 10:00
"LUNARDI(LOTTO4) ---- Here is a list of unavailable entities in your home: Netatmo La mia stanza, 4 L...

BotFather Mon
Inline mode is currently disabled for Messages_to_HA @Text_to_Ha_bot.

CD, 4 LU TUR CD, 4 LU TUR CD Battery Level" 10:00

December 6

"LUNARDI(LOTTO4) ---- Here is a list of unavailable entities in your home: Netatmo La mia stanza, 4 LU PF C Battery Level, 4 LU PF C Temperature, 4 LU PF F Battery Level, 4 LU PF F Temperature, 4 LU PF N Battery Level, 4 LU PF N Temperature, 4 LU TUR CD, 4 LU TUR CD, 4 LU TUR CD, 4 LU TUR CD Battery Level" 10:00

December 7

"LUNARDI(LOTTO4) ---- Here is a list of unavailable entities in your home: Netatmo La mia stanza, 4 LU PF C Battery Level, 4 LU PF C Temperature, 4 LU PF F Battery Level, 4 LU PF F Temperature, 4 LU PF N Battery Level, 4 LU PF N Temperature, 4 LU TUR CD, 4 LU TUR CD, 4 LU TUR CD, 4 LU TUR CD Battery Level" 10:00

December 8

"LUNARDI(LOTTO4) ---- Here is a list of unavailable entities in your home: Netatmo La mia stanza, 4 LU PF C Battery Level, 4 LU PF C Temperature, 4 LU PF F Battery Level, 4 LU PF F Temperature, 4 LU PF N Battery Level, 4 LU PF N Temperature, 4 LU TUR CD, 4 LU TUR CD, 4 LU TUR CD, 4 LU TUR CD Battery Level" 10:00

December 11

"LUNARDI(LOTTO4) ---- Here is a list of unavailable entities in your home: Netatmo La mia stanza, 4 LU PF C Battery Level, 4 LU PF C Temperature, 4 LU PF F Battery Level, 4 LU PF F Temperature, 4 LU PF N Battery Level, 4 LU PF N Temperature, 4 LU TUR CD, 4 LU TUR CD, 4 LU TUR CD, 4 LU TUR CD Battery Level" 10:00

December 12

"LUNARDI(LOTTO4) ---- Here is a list of unavailable entities in your home: Netatmo La mia stanza, 4 LU PF C Battery Level, 4 LU PF C Temperature, 4 LU PF F Battery Level, 4 LU PF F Temperature, 4 LU TUR CD, 4 LU TUR CD, 4 LU TUR CD, 4 LU TUR CD Battery Level" 10:00

December 13

"LUNARDI(LOTTO4) ---- Here is a list of unavailable entities in your home: Netatmo La mia stanza, 4 LU PF C Battery Level, 4 LU PF C Temperature, 4 LU PF F Battery Level, 4 LU PF F Temperature, 4 LU TUR CD, 4 LU TUR CD, 4 LU TUR CD, 4 LU TUR CD Battery Level" 10:00