博士論文（要約）

Research on Learning by Doing in the Operation of Building Systems: Comfort Scenarios in Data Supported Human-Window Interaction

（建築システムを「使いながら学ぶ」ことに関する研究：人と窓と間のインタラクションにかかわるデータに支援された快適シナリオについて）

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ABSTRACT

Our society is in constant transition towards sustainability and provision of comfort must be followed by a more conscious use of energy. Within building profession, this aspect is increasingly present among designers, whose intention is to implement low-consumption strategies to reduce energy demand without compromising the quality of the internal environment. However, reality often shows that technology-only design strategies are unable to solve such "wicked" problems. A frequently discussed solution is to involve end users in energy management and to provide comfort. Yet, such effort might be ineffective unless people decisions were supported by knowledge.

The research focuses on the long-term learning process of end users within the built environment. Of particular interest is to define how we can support traditional interaction between opening systems and end users during the operational phase. On the one hand, window systems and subsystems are important in the distribution of energy flows between the external and internal climate, which if well exploited could improve the quality of life and the performance of the building. On the other hand, the daily experience acquired through the senses are not always enough and the improper use of windows in favor of other active systems is very common. Consequently, the provisional information during window operation could trigger a long-term learning process and potentially improve natural ventilation in favor of comfort, the healthiness of the rooms and energy consumption.

To assess the effectiveness of information on human-window interaction, the author proposes the implementation of a window prototype. This device is dedicated to show real-time information about natural ventilation addressing different scenarios. Eventually, its impact is tested in the field with the participation of volunteers.

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CHAPTER I
INTRODUCTION

1.1. Research context

This research is fundamentally based on indicating the importance that the role of inhabitants assumes in the design of building systems. People's actions have a significant influence on building comfort and performances, and guiding them is a central aspect of sustainable design research and practice.

1.1.1. The behavior between sustainability and well-being

Our society is constantly changing towards sustainability. Buildings consume a quarter of the planet's energy resources and mainly depend on how they are designed, informed, and used. Given that it is people, not buildings that consume [1], learning how inhabitants interact with buildings is a crucial aspect as well as an act of responsibility by professionals towards improving the performance and design of buildings.

Consolidated habits accompanied by new technologies can lead to unexpected consequences. People have a great ability to adapt while achieving internal comfort. They can change environments to such an extent that they can harm themselves [2], and at the same time, their hedonistic behavior can satisfy the need for comfort at the expense of the environment.

In this context, technology and communication advancements should guide users to interact with architectural systems effectively and indicate a balance between these two extremes.

Understanding how people use buildings is an essential aspect of bridging the gap between project forecasting and actual energy consumption. In particular, pre-bound effects occur because individuals force themselves to consume less in inefficient buildings. For example, a 30% difference between ‘real’ consumption and design predictions was assessed in Germany [3]. In the meantime, rebound effects happen when families live inside efficient buildings but tend to consume more [4]. In this case, efficient systems often lead to higher consumption.

Involving end-users in energy problems or not depends on the researchers' studies and the interpretation of sustainability. While some authors suggest that the construction of buildings less sensitive to people's behavior is part of the solution [5], others argue that technology alone and stable conditions cannot solve environmental problems. This study considers that diversification of energy strategies allows people to build a more sustainable behavior based on greater engagement and a more shared ecological culture. To reduce the trend and achieve policy commitments, the whole society, architects, and general inhabitants must be involved at the same level [6].

1.1.2. Behavior and energy sufficiency

In 2013 the International Energy Agency (IEA) recognized the diversification of low energy construction strategies, which include measures of sufficiency, efficiency, and renewable energies [7]. While sufficiency addresses ‘energy needs’ or the energy necessary for a specific purpose, such as heating a room, cooking, or lighting, efficiency is related to ‘energy demand,’ referring to the energy required to operate equipment and technological artifacts [8].

T Pricen (2005) suggested that sufficiency aims at ‘enoughness’ while efficiency tends as much as possible with less. In other words, sufficiency addresses people's behavior and favors the reduction of energy needs, focusing "on the switch, not on the lamp" [9]. The promotion of sufficiency measures allows inhabitants' choices towards a more ethical use of natural resources. Furthermore, it can indicate alternative design decisions, identifying configurations to guide users' behavior towards energy saving implicitly. For example, a design decision could be to place the core of the staircase near the entrance to discourage the use of elevators or to make the windows equally accessible and usable by people [10].

There is also an order in the introduction of energy measures. Sufficient ones should come first to reduce energy needs before the introduction of more sophisticated technologies [11]. For example, in the Mediterranean region, buildings should be designed first to capture and store solar energy, and only if necessary, to support design with mechanical systems [12]. In this context, sufficiency measures naturally connect to the central idea of bioclimatic design.

1.1.3. Bioclimatic Design and the role of technology

The IEA indicates the bioclimatic project as a sufficiency measure to minimize the consumption of buildings [7]. It is a human-centered approach strongly correlated with regional climates and cultural differentiation. They argued that architecture should be connected to the local microclimate and aim at saving energy while maintaining comfort for the inhabitants.

Considering the definition of Architecture Institute of Japan (2010), it is an "architectural project conforming to the nature of the area and able to keep the global environment comfortable and pleasant for humans" [13]. Besides, the focus is on user awareness, and design should allow interaction with buildings through ‘life-size’ technologies [13]. In other words, its primary purpose is to provide inhabitants with accessible technologies for comfort and energy reduction, mainly by implementing measures of sufficiency and sustainable behavior.

From a bioclimatic design point of view, it is necessary to learn to live by interacting with the environment, culture, and local elements. In this regard, S Guy and G Farmer (2001) proposed to redefine sustainable architecture by considering six interpretations, which represent as many different sources of knowledge. The authors distinguished technical, centric, aesthetic, cultural, medical, and social perspectives [14]. Even if the authors did not express it directly, it is within the eco-cultural interpretation that bioclimatic design is placed. As the authors illustrate in this concept of place, human beings learn 'how to dwell' inside buildings that reflect the local cultural landscape and the bio-climate [14]. Therefore, comfort and energy reduction depend on effective interaction with the surroundings. For more information, 'Paper I' in 'Annex D' discuss more in deep the cultural dimensions featuring the bioclimatic design.

The following text highlights that indoor comfort is a complex and divisive topic, which involves the interaction of numerous disciplines such as thermodynamics, physiology, and psychology. Deciding on a particular approach implies a different idea of architecture, technology, and users.

1.2. The study of comfort in architecture

In this section, it is discussed the current approaches to thermal comfort within the environment. Each type of comfort index adapts to a particular architectural concept and the role of the different stakeholders during the design, commission, and operation phase. In particular, the adaptive method is proved to be capable of assessing comfort inside hybrid or naturally ventilated buildings.

1.2.1. Evolution of the concept of comfort

Over the years, in the architectural field, different interpretations and approaches to the study of comfort have followed. Already in 1936, T Bedford conducted field investigations describing the workers' satisfaction in British factories. The statistical methods inside his analysis employed a seven-value comfort scale still known today as the 'Bedford scale' [15].

The first to visually illustrate the relationship between climate and comfort for design purposes were the Hungarians Aladar and Victor Olgyay [16], dedicated to the study of the dynamics between climate, architecture, and human biology. During their activity at the University of Princeton, their diagrams, based on detailed climatic data, allowed to communicate professionally and socially the implications of the architectural form in the thermal equilibrium of the inhabitants, especially in a period when the HVAC system was spreading [17].

In Olgyay's theory, the comfort needs of people became part of the architectural discourse. In the book "Design with Climate" (1965), the bioclimatic and regionalist concepts were introduced, and thermal comfort recognized as the state of fundamental equilibrium to perform any other type of activity. People are said to benefit from a 'climate balanced' protective architectural environment around a stable comfort temperature [16]. This quality requires a more significant effort to design the building shape, shading, and orientation of the masses. In other words, by making the best use of the energies coming from the microclimate, the primary objective of architecture is to satisfy the occupants' biological needs.

From the 1970s, two approaches to thermal comfort have been developed in parallel. One is based on laboratory studies, while the other on campaigns conducted within real environments, in line with the Bedford method. Specifically, there are the physiological studies conducted by P O Fanger in climatically controlled rooms, and the adaptive method implemented by M A Humphreys, J F Nicol, and R De Dear (among others), analyzing the behavior of people in their daily habitat. The latter is a less invasive method which studies users in their typical habitat.

The scientific method proposed by Fanger indicates values for which, to respect the thermal balance of people within a 'comfort zone,' it is necessary to use energy-consuming solutions. Thus, it is considered useful for dimensioning HVAC. At the same time, the adaptive method demonstrates the complexity of comfort and the ability of people to adapt to varying conditions, and therefore to broaden the limits proposed by the scientific method. This aspect potentially reduces the use of active systems in favor of energy savings while maintaining comfort [15].

During the 90s, the problem of Sick Building Syndrome (SBS) became a central topic. This allowed the adaptive method to spread within the scientific research and the newborn PLEA (Passive and Low-Energy Architecture) because it reduces the use of mechanical systems in favor of naturally ventilated and, therefore, more sustainable buildings [15].

After a long debate, in 2004, the adaptive method was adopted in the ASHRAE standard and subsequently in other European standards. In recent decades, the work of the PLEA has contributed to the diffusion of the principles of bioclimatic design and, at the same time, the aspects related to adaptive comfort in architecture. Notably, the PLEA2009 held in Québec entitled "Architecture, Energy, and the Occupant's Perspective" summarized the reflections related to the responsibilities and autonomy of the inhabitants. The conference activities resulted in a list of five directives aimed at different actors. Specifically, the second refers to buildings that "should provide their inhabitants with multiple adaptive opportunities optimizing health, satisfaction, and productivity." In contrast, the third refers to inhabitants, who "should be responsible for taking an 'active' role for the provision of relative comfort using robust 'passive and low energy' strategies" [1]. The two directives underline the adaptive approach by linking the user's expectations in search of the objective of comfort with that of an architecture capable of providing 'in excess' the means to achieve it.

1.2.2. Different approaches to thermal comfort

The two approaches to the study of comfort seen previously reflect two perspectives that belong to the profession of the engineer, more specific, and that of the architect, who adopts a more holistic point of view [16]. Compared to the field approach, the laboratory provides more accurate results, allows the use of sophisticated systems, and conditions are the same for different volunteers [19], but it can deviate from the complexity of real scenarios. At the same time, the field approach, which involves the study of people in their daily habitat, tries to embrace the complexity of comfort, but it is more difficult to prove mathematically [20]. Finally, regarding comfort evaluation, in the laboratory method, thermal comfort means the stability of thermal conditions, while the adaptive approach welcomes indoor variation.

There are currently numerous indexes aimed at describing the relationship between physiology and thermodynamics. S V Szokolay (2004) recognized at least 20 of the most widely used. In particular, he highlighted the method known as Fanger's Predicted Mean Vote (PMV), which is based on studies in climatic chambers that combine physiological data under stable conditions with surveys. Then, he indicated the following revisions given by the introduction of the Equivalent Temperature (ET) and the Standard Equivalent Temperature (SET), which add the impact of humidity in identifying the comfort zone [21].

The PMV is based on a complex thermal balance equation that combines environmental and subjective parameters: (1) air temperature, (2) average radiant temperature, (3) relative air velocity (4), vapor pressure in the air, (5) activity levels (*met*) and (6) insulation levels (*clo*) [22]. During the Fanger original experiment, a PMV value of 0 (between -0.5 and +0.5) on a scale of -3 to +3, coming from the average mark of 1396 participants, was considered a state of thermal balance and comfort [22]. Then, PMV was combined with another Predicted Percentage Dissatisfied index (PPD), which indicated the rate of people uncomfortable with the environmental parameters of the test.

Fanger's method was proven to be inaccurate in describing people's comfort conditions in naturally ventilated buildings. The study conducted by Cheung et al. (2019) through the analysis of thousands of comfort data extrapolated from the ASHRAE Global thermal comfort database II, which included different types of buildings and occupants, demonstrates the unreliability of the laboratory approach. The authors compared the values of the PMV-PPD scale with the scales of the Thermal Sensations Observed locally (OTS) and the Observed Average Mark (OMV) (see 'figure 1' (left)). The accuracy identified was 34%, which means that only one every three predictions was correct. 'Figure 1' (right) also shows that there is more distance between the Observed Percentage of Unacceptability (OPU) and the PMV than the OTS scale. Besides, the figure does not improve by comparing the various types of buildings, whether naturally ventilated, hybrid, or air-conditioned [23].

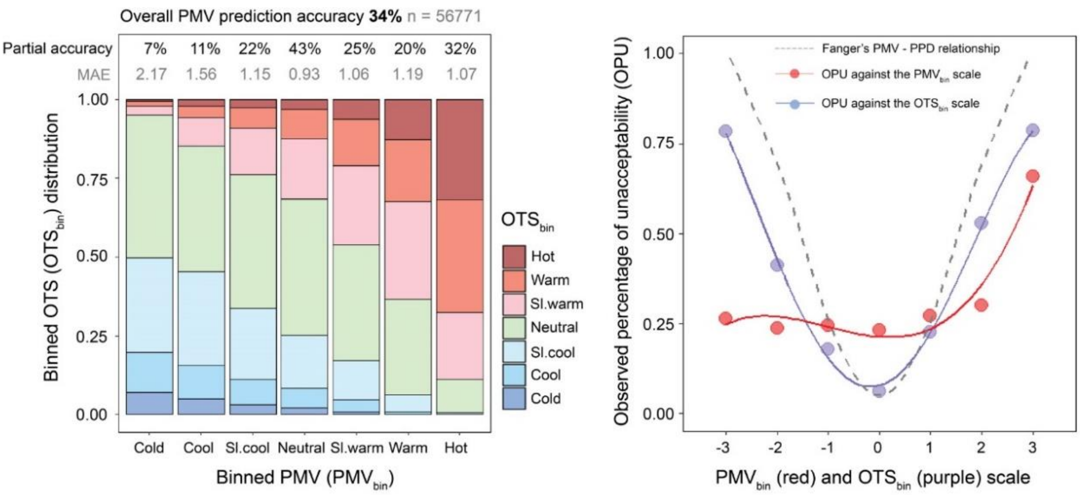


Figure 1. Relationship between OTS and PMV (left). General accuracy prediction and the correlation between OPU, PMV, and OTS (right). *From (Cheung et al., 2019).*

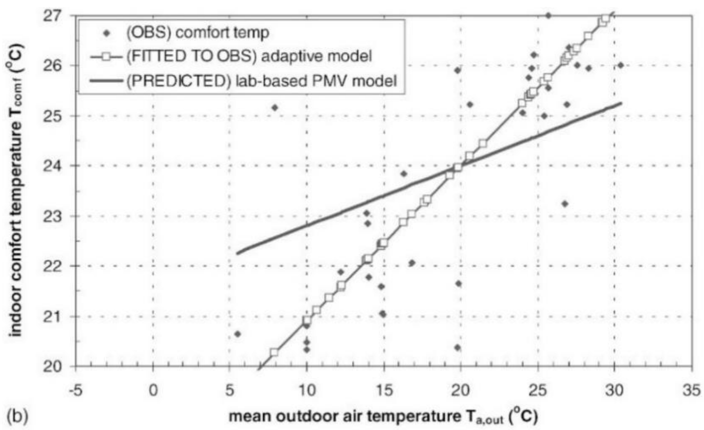


Figure 2. Correlation between comfort and average air temperatures in the adoption of the two comfort models in the study of naturally ventilated buildings. *From De Dear & Brager (2002).*

The authors concluded that considering the complexity of the proposed model, the PMV does not reach sufficient accuracy and that other approaches need to be found [23]. The errors could arise from the invariability of conditions or the lack of evaluation of the adaptive skills of people who are placed in an 'unfamiliar' environment [20].

Compared to laboratory studies, the adaptive method proves to be more reliable in describing comfort in naturally ventilated rooms. In a similar study conducted by De Dear and Brager (2002), thousands of raw data sets of office buildings from the ASHRAE RP-884 thermal comfort database were used, covering different climates around the globe.

The investigation showed that the comfort temperature is correlated with the outdoor air temperature average in naturally ventilated buildings and also air-conditioned ones (see 'figure 2'). In other words, PMV prediction sharply deviates from field observations based on the adaptive model [24], which is more indicated for studying comfort inside ventilated and adaptable buildings. The next table summarizes the main differences between the two approaches.

Table 1. Differences between the PMV and adaptive comfort method.

The PMV Method (P Fanger)	The adaptive comfort (F Nicol)
• More controlled data (scientific) • Comfort means the stability of conditions • Strict parameters bring to the use of HVAC	• Welcome complexity of reality (statistical) • Comfort means variability of conditions • Less invasive (analysis of people in their habitat) • More precise in defining comfort in NV buildings

1.2.3. Comfort in naturally ventilated buildings

The adaptive comfort approach considers the outdoor temperature as the primary parameter. In 1978, Humphreys indicated the relationship between people's comfort and outside temperature. The graph in ‘Figure 3’ uses two different equations for free-running and other types of buildings [20].

The two curves obtained through statistical regression from local observations demonstrate how the use of the monthly average of external temperatures is, on many occasions, a good enough method to give a prediction of comfort. Notably, the left curve represents non-free-running buildings, which confirms the adaptive principle of people connected to the exterior condition, indicating that "(...) in a building where the indoor temperature is decoupled from the outdoor temperature, inhabitants' comfort temperature will also be decoupled. Where the two are related, then so too will be the comfort conditions" [20]. However, since the method represents a ‘complex adaptive system,’ its verifiability is based on the conditions encountered locally, as in the case of the use of natural ventilation for comfort [25].

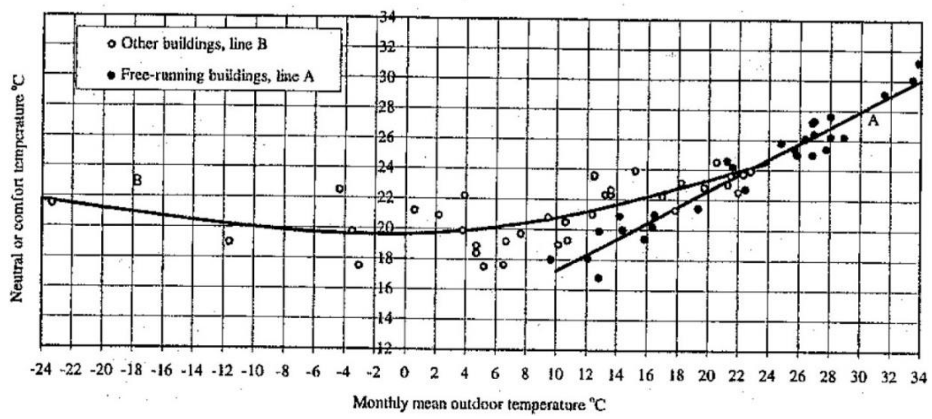


Figure 3. Correlation between indoor comfort temperatures and monthly mean outdoor averages. *From Humphreys 1978.*

Adaptive comfort is essential to study the impact of natural ventilation on the thermal balance, mainly for two reasons indicated by U Passe (2015). The first reason is that increasing wind speed allows extending the thermal comfort zone. Therefore, it goes in contrast with buildings with HVAC systems, where any air movement is avoided. In other words, the scenario is that people can adapt to the microclimate by opening a window. The second one is that adaptive comfort welcomes behavioral adaptations, recognizing that people change their clothing over time and depending on the seasons [26]. This aspect promotes the variability of indoor conditions, which is a fundamental aspect of naturally ventilated buildings.

1.3. Natural ventilation and user's control

This section is focused on describing the purpose of natural ventilation and the impact on comfort, health, and the fundamental role of users' adaptation within control strategies. Eventually, it is argued that pervasive sensing and automation can exploit people's creativity to yield more variable and comfortable indoor environments.

1.3.1. Scope and benefits of natural ventilation

One of the adaptive behaviors that modify the microclimate, comfort, and consumption is certainly the use of indoor ventilation. In the past, controlling ventilation was mainly used to expel carbon monoxide from the rooms. Nowadays, it is commonly adopted to improve Indoor Air Quality (IAQ) [26].

The Chartered Institution of Building Services Engineers (CIBSE) identified in ventilation the ability to "provide an appropriate level of IAQ by removing contaminants, and avoiding excessive energy loss [27]." Furthermore, in addition to the removal of Volatile Organic

Compounds (VOCs), it influences the thermal comfort and health of the inhabitants. Particularly, the air movement removes humidity, dilutes CO_2, and contributes to the cooling of the rooms through the decrease of temperature or by evaporation [26]. However, to achieve proper natural ventilation patterns, an integrated strategy is required, which also involves the planning of its control.

1.3.2. Natural ventilation inside design strategies

Choosing the type of ventilation strategy defines the end-user role and his degree of involvement in the control of building systems. Three ventilation strategies can be distinguished concerning the hierarchy of use and the degree of automation: 1) Air-Conditioning (AC), 2) Free-Running (FR), and 3) Mixed Mode (MM) [28].

While AC buildings rely exclusively on active systems, and FR ones on low-energy forces (as it happens with traditional buildings), the MM buildings are considered 'hybrid' or naturally assisted and aim to combine the benefits of the other two strategies. Also, hybrid buildings can be classified according to the spatial and temporal combination of solutions: zone, concurrent, and change-over. The ‘zone’ solution refers to a precise area of the building; ‘concurrent’ is related to providing natural and mechanical ventilation at the same time; and ‘change over’ recognizes the alternation of regimes according to the season [27].

In the context of adaptive comfort, the most effective trade-off is considered the hybrid solution, mainly due to the uncertainty of the climatic conditions and the real use of the systems. In this case, it is necessary to ensure that people have access to the opening controls or allow an 'override' of the system if automated.

Table 2. Ideal stages of a ventilation design process. *Adapted from Etheridge (2012).*

Stage	Comments
Feasibility	Assessing if natural ventilation is technically feasible
Definition of strategies	Defining how it can be achieved and controlled
Envelope design	Sizing the windows and define the control
Internal flow	Calculating the behavior of the internal flow
Commissioning	Checking commissioning and post-occupancy evaluations

The literature relating to natural ventilation considers the compliance with the following ideal stages inside the design process [28]: 1) feasibility, 2) definition of strategies, 3) the design of the envelope, 4) the study of the internal flow, 5) commissioning (see 'table 2'). The adoption of one or more stages is commensurate with the type and complexity of the building.

Already in the feasibility stage, after analyzing the climatic patterns, the boundary conditions, and the regulatory context [29], considering the level of user involvement is a fundamental aspect to be evaluated for the effectiveness of the strategies [27, 28]. From this aspect, it depends on the control methods and how to set the ventilation flows. Additionally, if a building is designed to provide ventilation naturally, the air must be provided through appropriate windows [30], which can be assisted, for example, by the presence of solar chimneys or ventilation towers, among other systems.

1.3.3. Main functions of operable windows

The window is among the most studied devices within adaptive processes. Its operability allows mediation between internal and external environments and offers the user the choice between a connection or a barrier from environmental factors [31]. For this purpose, windows work in conflict with microclimate, envelope, and structural systems. As J Cremers (2016) pointed out, "Building openings define the transition from introverted to exposed, from warm to cold, from artificial to natural, from dark to light, from enclosed to open space" [30]. An example is the need to exchange the air and, at the same time, to maintain internal heat during winter.

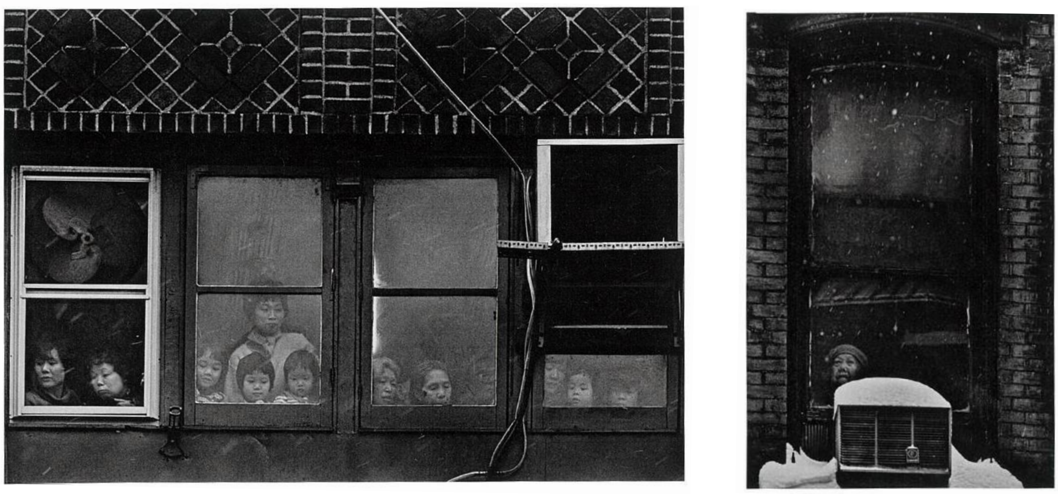


Figure 4. Photos representing human-window interaction and the concept of the window as a filter between inside and outside. *Photo by G Masao, 'from Window Series' (1972-1990), inside the book of the exhibition 'The Window: A Journey Through Art and Architecture Through Windows'* (32) *(2019).*

The nature of the conflict arises from the integration of multiple functions into a single building system. Among the functions of a window, there are light and air connections with the outside. Another additional one is allowing people to physically connect with the exterior, "sticking the head out" [33]. Regarding the latter, it is continuously suggested that user satisfaction is linked to the possibility of giving rise to this connection. People need contact with natural events and the passage of time, to unwind and get out of their system, or simply to feel the breeze and noise of the outside world [33]. Therefore, windows are a fulcrum between the changeability of natural elements, things, and people (see 'figure 4') [34].

Table 3. Primary and secondary functions of a window. *Adapted from Cremers (2016).*

Primary functions	**Secondary functions**
Entry and exit	Use of daylight
Extensive opening	Eye contact
Passage of matter	Energy generation / conversion / conservation
Ventilation	

Window position	**n[1/h]**	**Time of air exchange [min]**
Closed	0-0.5	>120
Tilted	0.3-4	45-75
Half-open	5-10	6-12
Completely open	8-15	4-8
Completely open cross ventilation	>20	<3

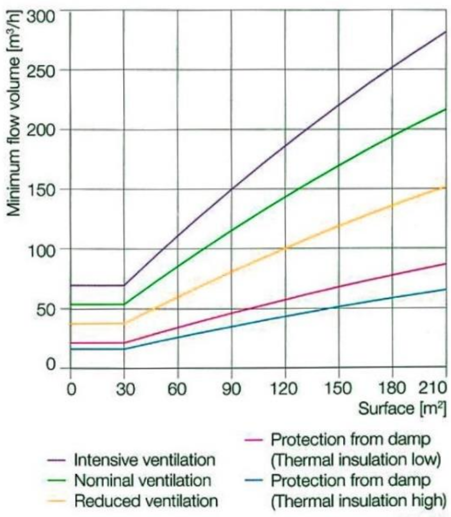


Figure 5. Air change rate depending on the window opening angle, and typical flow rates of different types of ventilation inside buildings. *Adapted from Cremers (2016).*

It is generally possible to identify in the permeability an intrinsic quality of openings. The operation of a window is not based on simple 'open/closed' but allows the graduation of the permeability of the envelope. It can be the permeability to electromagnetic radiation (light and heat), materials, or things (gas, particles, insects, et cetera), wind, sight, heat, and sound waves, and finally, people [30]. The permeability to ventilation is indicated among the primary functions (see 'table 3'). Specifically, the graph in 'figure 5' shows different types of ventilation inside buildings, while on the right, it is described that the duration of the air changes according to the position of the window. From the comparison of the two data, the windows are indicated to create intense exchanges of air volume by reducing the exposure to internal pollutants and the loss of heat from the surfaces. As a result, window operation is central in comfort and health.

As discussed in the next subsection, manual adjustment of ventilation permeability and user involvement are irreplaceable elements considering window use (see 'figure 6').

Figure 6. Permeability to ventilation as the primary function of the window. Installation of Roman Signer 'Window Shutters' (2012). *Photos of the author from the exhibition 'The Window: A Journey Through Art and Architecture Through Windows,' Tokyo (2019).*

1.3.4. Difficulties in replacing manual control

Controlling the permeability allows users to adapt the internal environments to the ever-changing external context. Notably, the air permeability of a building envelope can only be managed through the kinematics of translation and rotation of one or more levels (oriented parallel or perpendicular to the facade plane). Always Cremers argued that "no other technical solutions are currently available that allow a building to 'breathe' in a controlled way through an envelope permeable to air while also meeting all the demand made on it using other strategies" [30]. In other words, he highlighted the centrality of windows in graduating indoor/outdoor connections. Furthermore, the manual operation of windows has various advantages in terms of comfort provision and conflict management.

First, the manual operation requires the occupant presence. This aspect brings the target of the ventilation (end-user) near the window, facilitating the design objectives. Moreover, it permits to adjust window permeability to the real-time needs of users. For example, they can operate windows with millimeter precision and facilitate "sufficient enough" behavior favoring energy savings. Additionally, they can quickly solve conflicts caused by noise or bad weather.

On the other hand, fully automatic systems can adopt programmed opening and are useful to operate far-reaching windows (see 'figure 7'). However, their adjustment can result too coarse or displaced in space and time to address the real comfort needs of individuals. Furthermore, as suggested by R Cohen et al. (1998), full automation might leave a window open to fumes, noise, cold or heat, and insects [35]. The trade-off between the two approaches is often considered to permit people to override automatic control, and that user behavior should be informed enough to manage the conflicts.

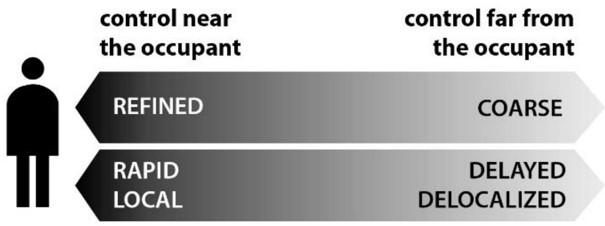


Figure 7. The implication of manual and automated operation in window position and opening.

Table 4. Types of windows compared to environmental conflicts. *Adapted from Cremers (2016).*

Window type	Outside is raining	Outside there is traffic	There are other interacting elements	Effective opening area	Good for fast ventilation	Good for slot ventilation	The wind is banging the shuts
Horizontal pivot	○	●○	○	100%	●●	●○	○
Vertical pivot	○	○	○	100%	●●	●○	○
Top hung	●●	●● (internal)	●○ (internal) ○ (external)	No free opening	○	●○	●● (with additional fitting)
Bottom hung	●● (internal) ○ (external)	●●	●○ (internal) ●● (external)	No free opening	○	●○	●● (with additional fitting)
Side hung (casement)	○	●● (internal)	○ (internal) ●● (external)	100%	●●	●○	○
Tilt and turn	●● (tilt internal)	●● (internal)	○ (internal) ●● (external)	100%	●●	●○	●● (with additional fitting)
Sash (sliding)	○	●●	●●	50%	●●	●●	●●
Projecting	●○	●● (internal)	●● (internal) ●○ (external)	No free opening	○	●●	●●
Louvers	●●	●●	●○ (internal) ○ (external)	Free opening	●●	●○	●● (with additional fitting)
○ No; ●● Good; ●○ Limited							

The conflicts related to ventilation and weather protection variate depending on the disposition of the protective layers and the geometry of the window [30]. 'Table 4' illustrates different opening geometries and the relationship with ventilation capability and rain protection. Most of the conflicts indicated are managed by the users or are solved during the design stage.

In this thesis, it was taken the example of side hung windows. The choice was mostly due to the opening area available on the building facade used for the tests. In this case, a sliding opening would have reduced the inlet area by about 50% due to the permanence of the door inside the compartment. Subsequently, a door projecting outward helped to keep the window closed in the presence of strong wind pressures (performed in ventilation tests). Eventually, for the outside raining protection, I opted for the application of barometric sensor readings to inform the user of future weather changes.

Another limit considered by the thesis was referring only to a condition of one small/medium size room with one operable window and one door, which is a typical 'concurrent' and 'change-over' situation in Japan. The management of conflicts and opportunities coming from a connected system of multiple openings was not part of this study, but a possible focus for further research.

1.3.5. Mixed-mode adaptation towards sustainable comfort habits

The point of view of this work was that informing and involving people's creativity comes from the direct use of building systems. As discussed in the next chapter, extending Human-Computer Interaction (HCI) studies to embrace the built environment implies the interactivity with indoor comfort and considering the variability of environmental conditions [36]. Furthermore, the object surrounds the users for the fact that the interaction involves systems embedded in the built environment.

The design of embedded feedback systems takes the human perspective and the overall experience that leads to human-building interaction. 'Figure 8' (see on the next page) is a synthesis of the role of individuals between automation and sensing technologies and building systems. It illustrates that people balance energy and comfort based on their capability, opportunity, and motivation. As defined by S Staddon et al. (2016) "Capability refers to Physical and Psychological aspects of an individual's capacity to engage in the behavior concerned, Motivation refers to Automatic and Reflective brain processes that energize and direct behavior, and Opportunity refers to external factors that are Physical and Social factors in and which supporting the behavior" [37]. These three aspects could be reinforced through proper design techniques, giving individuals the possibility to act in mixed-mode adaptation, guided by their feelings but also by provisional information from pervasive sensor networks.

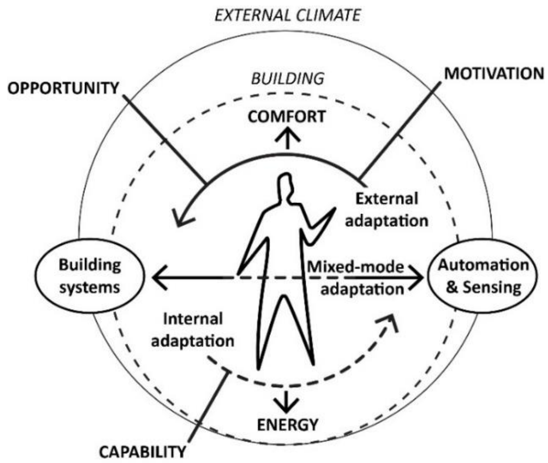


Figure 8. Users' Mixed-mode adaptation to balance indoor comfort and energy.

1.4. Informed behavior with windows

From the moment when it is recognized the user the ability to react and alter the environment through their choices, informing their action suddenly becomes a central aspect. The success and long-term effects of communication strategies depend on the role of the user and the timing of information.

1.4.1. Increasing individuals' knowledge and motivation

Users' role inside the built environment is strictly linked to preconceptions towards comfort. It starts from end-users themselves but also depends on how designers define their strategies and shape their buildings. A building that autonomously solves comfort issues is a perfect situation for passive users, who expect nothing but stable conditions and no personal actions. Then, the ideal 'adaptive scenario' is that the inhabitant automatically reacts to the discomfort caused by external stimuli, without any further motivation. However, while 'passive' occupants do not act, "adaptive" users react by taking on the tools provided by the designers, people, in general, can meet new meanings and alter their role if necessary. In other words, people can learn new habits or change previous ones considering newly acquired knowledge.

Furthermore, this change can happen simultaneously in the same subject or considering different environments (see 'figure 9' on the next page). For instance, passive use can be found in a factory or during a wedding ceremony [38], but especially in residential buildings, people "leave the doors open, generate body heat, maintain pools of tropical fish and install plasma

TV screens" [6]. In short, it is not only necessary to provide information to users or to expect them to react to 'adaptive opportunities.' It is also necessary to motivate them via meaningful long-term learning experiences.

Guiding user behavior to match design intentions is a difficult task. Psychology and information studies already identified the presence of gaps between knowledge and action. Since the users do not absorb all the given information and their intentions not always lead to sustainable decisions, the designer must adopt various techniques to 'bridge those gaps (see 'Annex D' for more information).

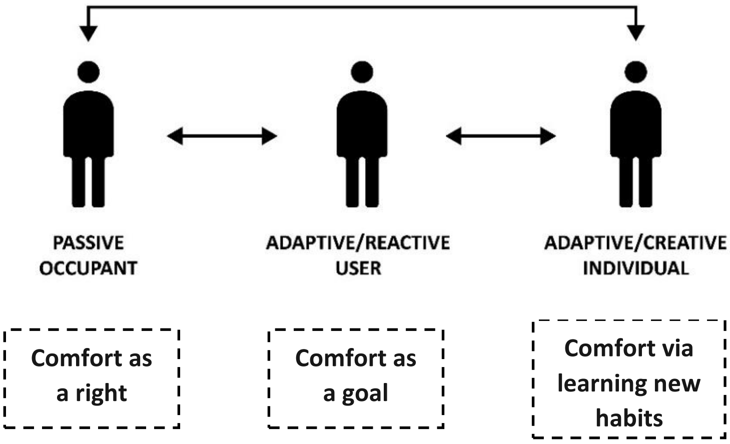


Figure 9. Change of the inhabitant's role based on the situation.

1.4.2. Reaching end-users during building operation

To address not only energy-related issues but also long-term sustainability, people should learn gradually. Many authors believe that short-term environmental attitudes based on extrinsic motivations do not last, and that sustainability requires long-term commitment [39]. For example, van der Linden (2015) argued that continuous motivations are needed. In fact, in his case study, during a national competition for the reduction of energy between university students, electricity consumption decreased over a month (the duration of the event). However, about ten days after the consumption of the experiment, they returned to normal.

Furthermore, 'figure 10' (on the next page) indicates the occasion when stakeholders generally improve their knowledge regarding building design. End-users (usually not involved in the design process) acquire most of the information during the operation phase. Consequently, to obtain a long-lasting impact on comfort and energy reduction through window interaction means that a device capable of yielding meaningful information all along building operation is needed.

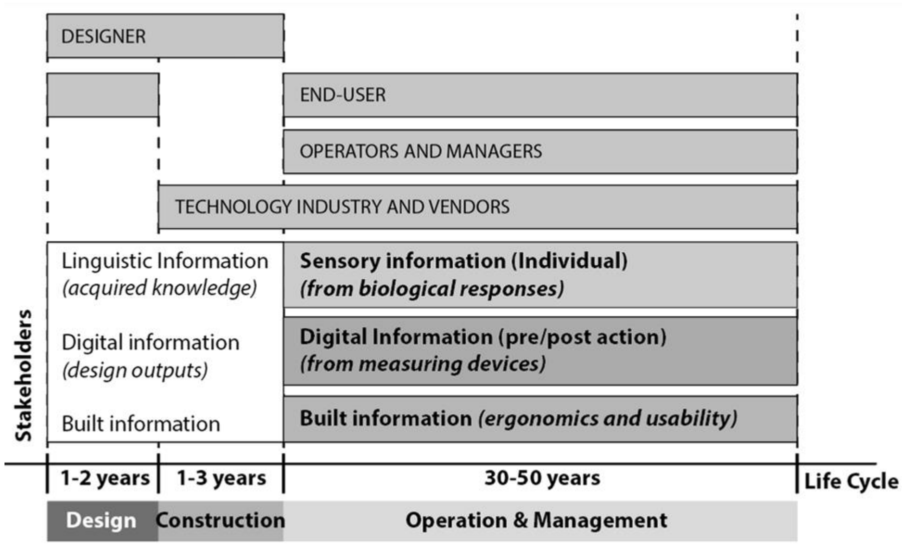


Figure 10. Information provision during a building life cycle. *Adapted from Ackerly (2012).*

1.4.3. Previous experiences on informed behavior with windows

The literature related to the impact of information on human-window interaction in the field is not very extensive, especially for the aspects concerning health and comfort. The collected studies illustrate the use of signaling systems dedicated to alert users about the excess of CO_2 and high temperatures; shading displays showing environmental information on the glass; multi-function windows linked to a monitoring system of real-time environmental parameters, and an interactive smart window.

Figure 11. Window opening signaling systems based on environmental parameters. *From Ackerly and Brager (2012).*

First, K Ackerly (2012) investigated persuasive opening/closing signaling systems alongside the windows, which respond to external and internal parameters such as IAQ, temperature, humidity, and wind speed [40]. Based on the identification of 16 high-performance mixed-mode offices and by formulating inquiries, interviews, and site visits, the author focused on the impact of signals on the individual and collective use of windows inside the open-space offices (see 'figure 11'). Eventually, the study highlighted how the alerts could provide a better understanding of the built environment and the contribution of the openings on comfort; give a greater awareness of the external microclimate; increase the ability of occupants to predict future inconveniences [41].

In a more recent investigation, P Bader et al. (2019) described a window system that informs users of environmental aspects. The system, called *WindowWall*, took advantage of liquid crystals as shading systems that alter window transparency to light. In the meantime, the display could draw symbols to inform users about calendar events, private messages, but also weather information (e.g., weather and temperature, with also the help of colored lights), as illustrated in 'figure 12' [42]. Although the example represented the possibilities of environmental information displayed by window systems, it lacked in connecting the data to open/close action, comfort ventilation and air quality, which are essential aspects concerning window operations.

Figure 12. Weather information displayed by the WindowWall system. *From Bader et al. (2019).*

Another recent investigation showed the development of a multi-function smart window prototype connected to a control system. The window monitored CO_2 levels, humidity, temperature, and VOCs concentration in the environment, and it was equipped with PV louvers connected to an integrated ventilation system. Eventually, the study demonstrated the system's energy efficiency and the return on investment and developed real-time monitoring software plotting the data from the environment [43] (see 'figure 13'). However, it was designed for automated ventilation without providing end-users' interaction. Additionally, the study did not indicate the strategic positioning of the sensors inside the prototype, or the type of VOC analyzed.

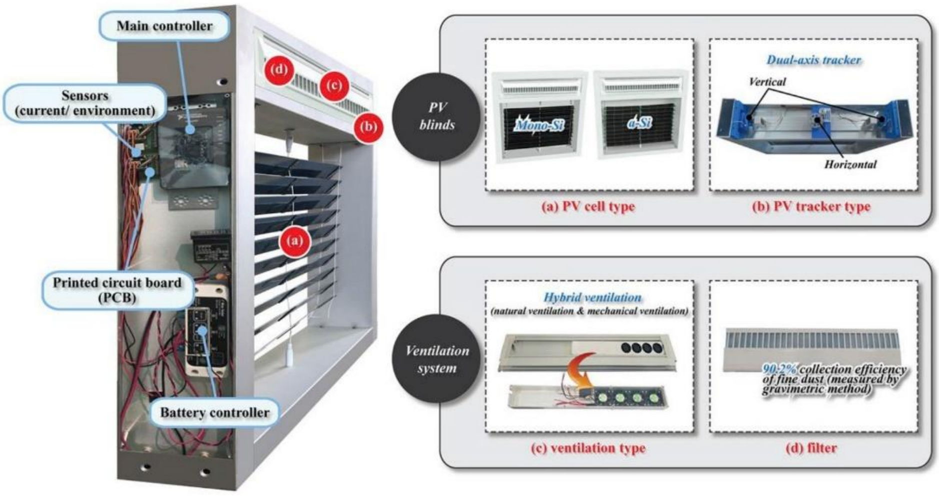


Figure 13. A prototype of a multi-function smart window for ZEB buildings. *From W Jung, et al. (2019).*

More advanced approaches outside the academic sphere confirmed the manufacturers' interest in information and natural ventilation linked to windows. YKK AP, a Japanese company leader in the sector of locking systems, plastic hardware, industrial machinery, and architectural products including windows, developed a conceptual model called Module Window (M.W.) part of the MADO Project started in 2016 (see 'figure 14') [44].

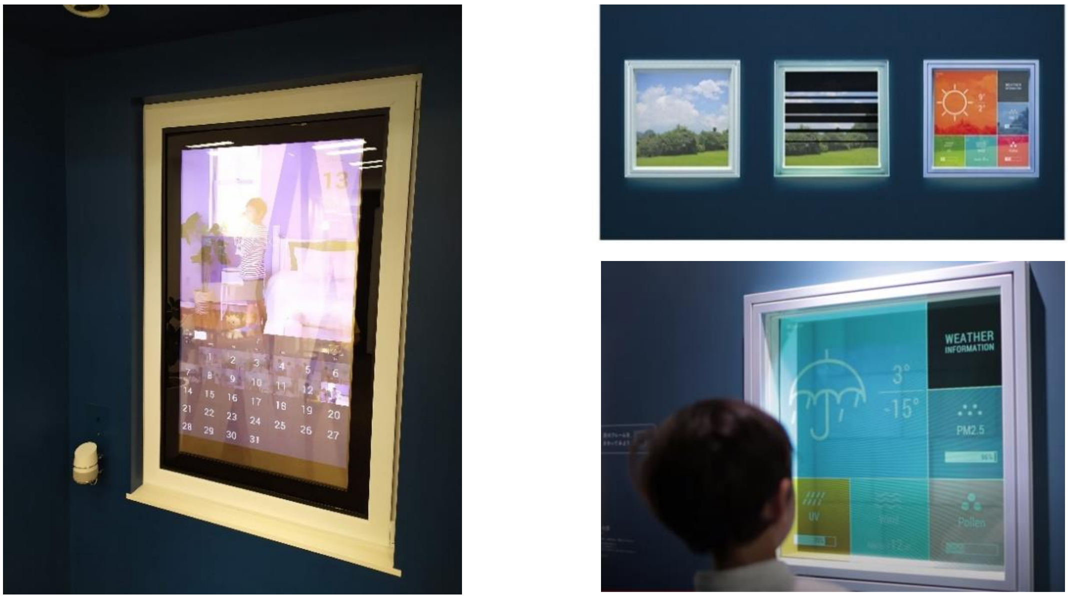


Figure 14. The prototype of the Module Window during an exhibition (left). *Photo from the author.* Demonstration of the window functions and data display (right). *From http://module-window.jp/.*

The project aimed to improve human-window interaction by showing environmental data with integrated monitoring systems. Additionally, it consisted of an automatic ventilation system responding to the state of the air inside and outside, and a digital solar shielding (among other services) [45]. The module demonstrated the interaction capabilities through tactile gestures for accessing information, Zero UI during window opening, and the visualization of data in transparency through the glass [46]. Nevertheless, it did not involve the users in comfort management or guide them providing, for instance, real-time wind data and CO2 measurements.

1.5. Problem definition

In the previous sections, it is recognized the centrality of users in terms of comfort provision. It is also argued that for the positive outcomes of natural ventilation strategies and window operation, behavior based on newly acquired knowledge becomes necessary. Furthermore, considering the various types of learning approaches, the long-term learning experience is the most effective.

However, based on previous design examples, there were not enough studies that demonstrated how to improve comfort with windows in favor of ventilation and how to build a useful interaction model practically. Specifically, the author did not encounter enough research focused on expanding adaptive opportunities with windows, and thus triggering a learning process based on detailed and real-time information related to ventilation, air quality, and perspectives of thermal comfort. Consequently, the primary issue that triggered the research was:

"*Could a window system improve the connections between the search for comfort, the environment, and people's energy consumption?*"

Subsequently, I considered what would happen to comfort and energy consumption if environmental information commonly difficult to perceive was provided to the user during the daily use of the window. Moreover, how could I prepare a '6-senses' interaction between individuals and windows? Then, how could I represent comfort advantages coming from a learning process based on the personal use of windows? This series of questions led to the formulation of the following research hypothesis:

"*Thanks to provisional information in favor of natural ventilation provided by the window system, it could be triggered a 'Learning-By-Doing' process that increases adaptive opportunities, indoor comfort, and consequently reduce consumption.*"

1.6. Motivations for the research

Understanding how to design less energy-consuming, comfortable, and healthy environments is the basis of the profession of architect in the near future. Therefore, a central aspect was defining what the real comfort needs of people are within their usual habitat, and how they adapt the built environment to the changing conditions of the climate. In particular, it was central to understand the impact of user's decisions in window use to take advantage of the adaptive behavior of people inside design strategies. ‘Figure 15’ indicates the main points of interest: 1) why people change their role from passive to creative; 2) the relationship between human attitude, the microclimate and the new information and communication technologies available to architects; 3) the impact of windows operation on the indoor environment; 4) the integration of ICT systems inside windows and the modalities to assess their functioning.

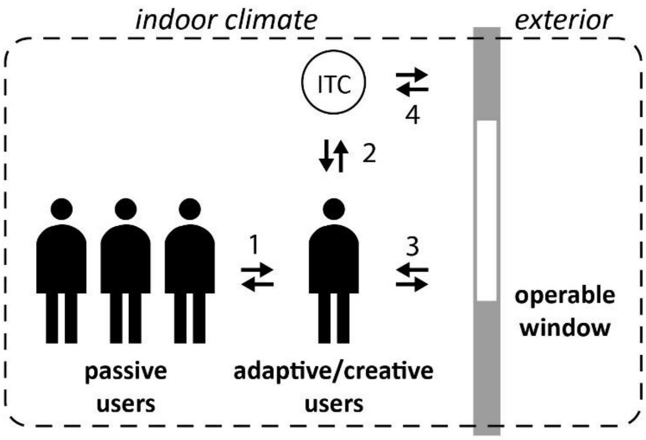


Figure 15. Main points of interest in the thesis.

1.7. Research objectives and methodology

The objectives of this investigation were oriented to inform architects on the capability of ITC systems in increasing comfort with windows. In particular, the research aimed to:

- Discussing how feedback technologies can increase awareness about indoor comfort;
- Discussing traditional interaction with windows and learning opportunities;
- Identifying feedback parameters and modalities that can support people towards their comfort goals;
- Demonstrating how a window system based on feedback technologies can inform a Learning-By-Doing process on natural ventilation.

The methodological approach of this research was unusual in several respects. The research combined the method of theoretical study, literature review, and field tests, with the creation of a concrete design object as a means for detailed investigations. This choice guided many of the decisions taken in the testing phase and oriented the research towards a more practical, interdisciplinary, and design-oriented approach.

To address the main hypothesis, I devised a new window based on a closed-loop system with setpoints, user involvement via User Interface (UI), and configuration for real-time monitoring of natural ventilation and other environmental data relating to thermal comfort. The primary function of the window was to connect CO_2 decrease to the manual adaptation of ventilation and facilitate the achievement of comfort through a long-term learning process. Finally, I created a prototype, which implemented the main theoretical concepts, and organized a case study, demonstrating the system's impact on the initial learning process towards comfort.

Compared to studies dedicated to natural ventilation with windows, tending, for example, to the analysis of cross ventilation and air flows and how pollutants are dispersed, the study aimed to discuss the impact on comfort and the benefits deriving from the control of ventilation. At the same time, compared to human-building interaction studies, it was more tied to the psychological aspects deriving from the perception and control of the environment and use interface, rather than studying forecasts on consumptions. However, the results could inform statistical studies and Building Performance Software (BPS) regarding the use of advanced window systems.

1.8. Thesis structure and organization

The investigation was based on the Learning-By-Doing concept. Inside this context, I discussed the enhanced human-window interaction via long-term learning on comfort (see 'figure 16').

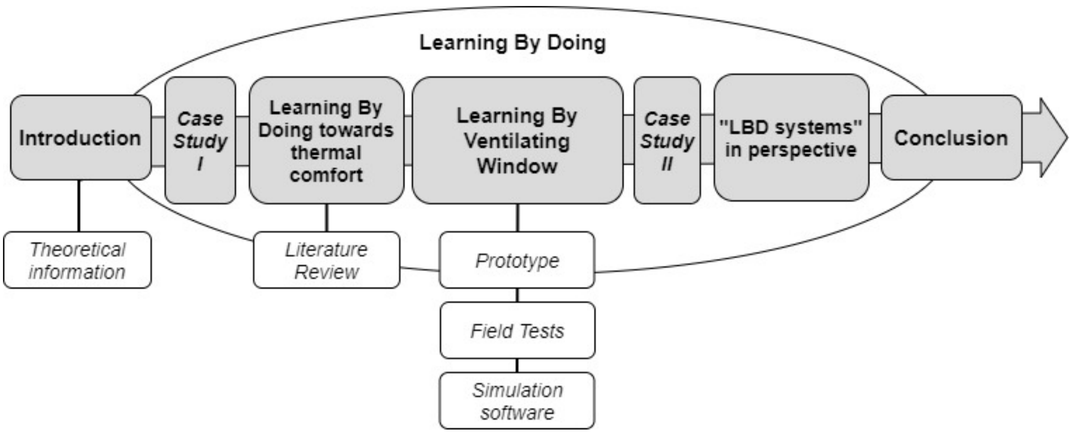


Figure 16. Scheme of the structure of the thesis.

A qualitative case study gave the initial step. Then, a literature review was performed to explain what triggers the interaction towards windows and the learning opportunities of interface design. In the central part of the thesis, the discussion focused on the concept of the Learning-By-Ventilating Window.

To implement it, I conducted field tests to guide the design of a window prototype and the refinement of software that simulates the behavior of the window interface. Further field tests demonstrated the capability of the prototype in collecting environmental data. Then, a human-window interaction algorithm defined the main path of actions that could be addressed by the window. Eventually, a second qualitative case study was organized to assess the initial learnability of the system. At that stage, people were involved in the use of the prototype, and their learning process was demonstrated via comparison with informed/non-informed behavior. The algorithm and the results of the 'Case Study II' helped to individuate future possibilities of similar LBD devices and to conclude the investigation.

1.9. The originality of this work

The research considered describing people's interaction with windows, which is a diffused topic inside occupant behavior and adaptive comfort studies. The contribution of those investigations was meaningful to understand which contextual factor triggers people's adaptation and the consequences of their choices in comfort and energy consumptions. However, they lacked in describing why people act in a certain way and what designers could do to increase user adaptation with windows.

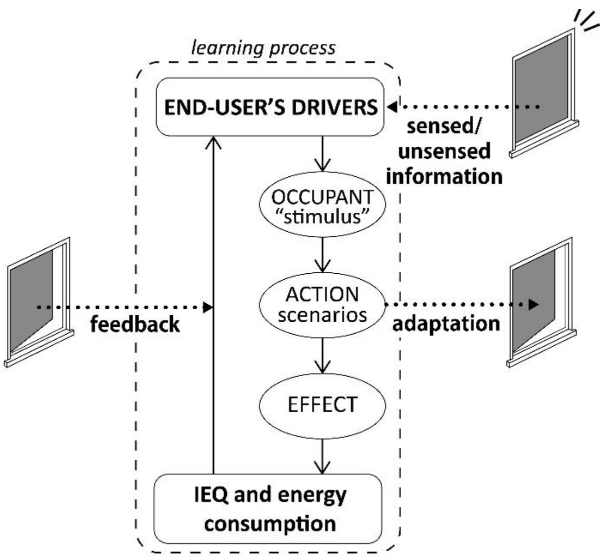


Figure 17. From end-user drivers to Indoor Environmental Quality. *Adapted from Fabi et al. 2012.*

The originality of this dissertation stands on the tentative to expand adaptive opportunities ideating, prototyping, and testing a device dedicated to informing users on ventilation strategies for comfort. It could be contradicted remembering that HCI researches already offer many viewpoints on the modality of creating interactive tools based on the feedback information. Nevertheless, very few of them reach the ‘size’ of building components, and far fewer are those dedicated to improving adaptive thermal comfort. Eventually, the research promoted the discussion regarding the interaction between informed users and window systems.

The outcomes might inform occupant behavior studies on the impact on comfort and consumption of learning processes by the use of feedback from window systems. In this perspective, 'figure 17' synthesize the learning process proposed in this thesis. From the traditional end-user drivers to interaction, a sequence of stimulus, action (including window adaptation), and effect, lead to the alteration of Indoor Environmental Quality (IEQ) and energy consumption. Inside this cycle, the window system could produce information and feedback as new drivers to promote better environments via a long-term learning process.

CHAPTER II
LEARNING BY DOING TOWARDS INDOOR COMFORT

2.1. Introduction

This chapter focuses on the human mechanisms of thermal balance and adaptive comfort. People's behavior is illustrated based on environmental perceptions. Afterward, 'Case Study I' analyses how a group of people perceive climate variations, indicating parameters that are less recognized than others. Those aspects are considered central within the learning process for comfort. Finally, the thesis goes forward, noting how technology could support people in helping environmental perceptions and, consequently, their comfort achievement.

2.2. Biology and relationship with the microclimate

Human thermal balance is based on inner and outer mechanisms that help the body maintain stable conditions. This section discusses those mechanisms and how it is possible to connect thermal comfort to the local climate.

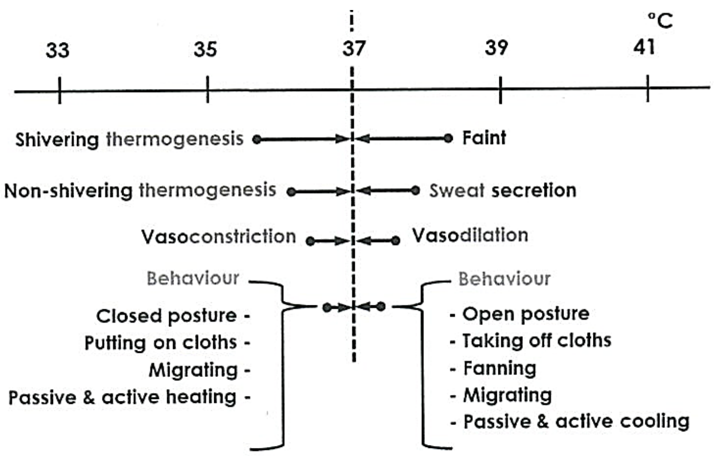


Figure 18. The adaptive mechanism to maintain homeostasis inside the human body. *From Shukuya (2019).*

2.2.1. Human reaction to the microclimate

The human body continually receives information from the environment. This information generates patterns of sensation, perception, and behavior that allow the body to maintain its thermal balance or homeostasis (see 'figure 18'). According to M Shukuya (2019), discomfort is the basis for adaptive actions, and they are not necessarily reflected in a change of environment, but also performing physiological reactions. In particular, when behavioral adaptation such as changing posture or putting on clothes is not enough to maintain 37 °C of the internal core, the organism reacts with an involuntary mechanism that ranges from vasoconstriction to shivering or sweat secretion [47].

ASHRAE considers thermal comfort a condition of mind and argues that the body is an extension of the brain. The skin is the sensory portal that connects somatic (voluntary) information to the spine connected to the nervous system. Especially, the information related to heat is interpreted inside the limbic system of the brain, while behavior and lifestyle are generated in the more advanced part of the frontal cortex [48].

The adaptive comfort arises from the interaction between behavior and construction and is based on the 'adaptive principle' that “if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort” [15]. The interaction with the external environment is triggered by environmental factors that produce discomfort cycles (as a matter of fact, it could be referred to as adaptive 'discomfort').

The approach considers the biological point of view that the human being is a 'comfort-seeking animal' who seeks 'adaptive opportunities' and interacts with the environment through a series of actions to restore comfort. These actions are innumerable and vary from changing the environment to changing one's behavior. In other words, as depicted in 'figure 19', it is considered a cyclical process that starts from a feeling of discomfort, and that drives the body to adapt internally and externally to regulate the sensations. Shukuya argues that physical adaptation is manifested when inner behavior cannot regulate the temperature automatically.

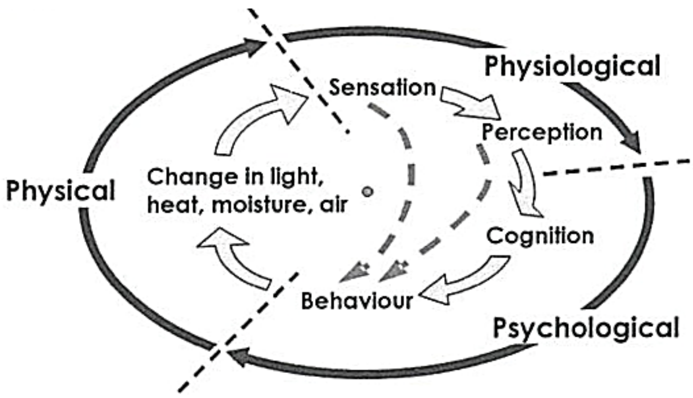


Figure 19. The adaptive thermal comfort as an inner and outer cycle of sensations and behavioral reactions. *From Shukuya (2019).*

As previously mentioned, the adaptive method suggests using the average of the external temperatures to determine the comfort temperature. It happens mainly in free-running buildings, where people adapt biologically to the climates in which they usually live and experience monthly climate variations. Therefore, outside temperatures are the necessary parameters to measure indoor thermal comfort.

2.2.2. Measuring comfort in naturally ventilated buildings

The human body balances thermal sensations considering a series of objective and subjective parameters, which change depending on the climate context. The basic equation that relates them to thermal balance is the following:

$$M\text{-}W = C + R + E + (C_{res} + E_{res}) + S$$

Where *M* is the metabolism of the person, and *W* is the work produced. Then *C*, *R*, *E* are the convective, radiative, and evaporative heat loss from the body with clothes, respectively. Then, *S* is the rate of heat storage by the skin. Finally, C_{res} and E_{res} are convective and evaporative heat loss that comes from respiration [20]. Other subjective parameters, such as *met* and *clo,* are considered difficult to control and less treated inside this thesis.

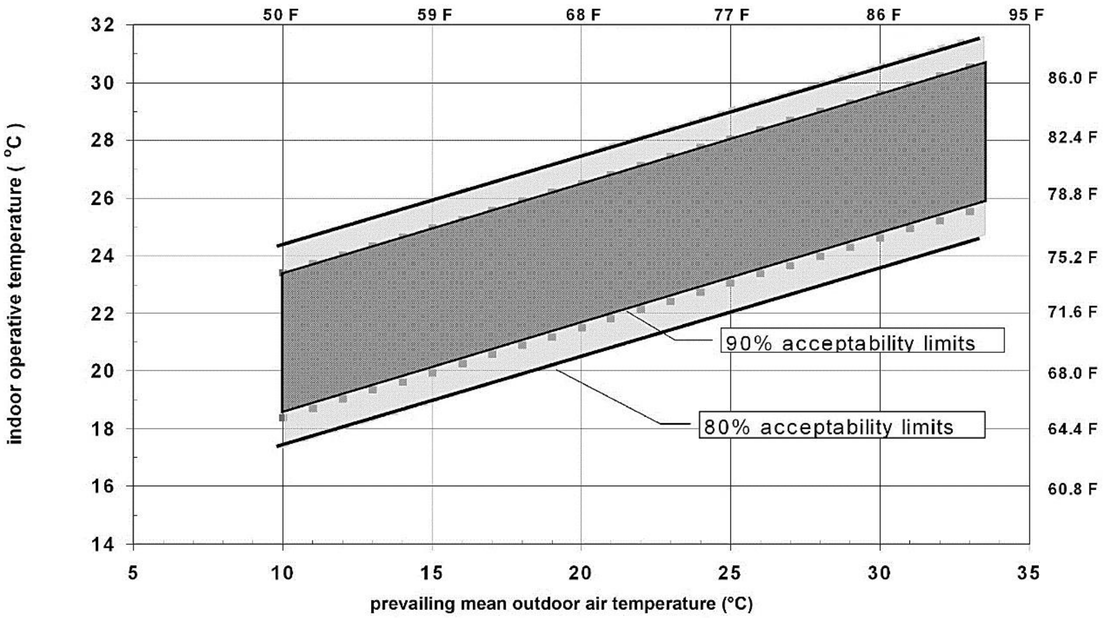


Figure 20. Comfort zone inside naturally ventilated buildings. *From ASHRAE 55/2017.*

An essential parameter is the operative temperature that combines radiant and ventilation effects. This value is highly relevant, considering the equation. Comfort and thermal sensations largely depend on the heat emitted by the surfaces surrounding the user, and the impact of ventilation in evaporation rates increases the possibility of obtaining comfortable environments. Therefore, in the evaluation of adaptive comfort, the relationship between the operating temperature and the average outdoor temperature is among the best indicators (see 'figure 20').

In the meantime, the method recognizes the complexity of measuring comfort in the field and utilizes a statistical approach for more in-depth evaluations.

2.3. Case Study I: analysis of the sensory abilities of a group of people

A field test study was performed to test people's ability to perceive the variation of environmental aspects and to be able to indicate particular aspects to be supported in an informed operation towards comfort. It was organized into four phases:

1. Local climate data collection;
2. Analysis of the microclimate of the test room, without people;
3. Carrying out the test with a survey on comfort and sensations;
4. Analysis and discussion of the results.

The general condition was monitoring a group of people during routine activities inside a naturally ventilated meeting room. Particular attention was paid to conduct non-invasive measurements, and in controlling as much as possible the variation of environmental factors during the weekly meeting sessions. Then, the same meeting room was reused for other tests before the realization of the window prototype.

2.3.1. Local climate data collection

The Tokyo climate data were retrieved from the Japan Meteorological Agency (JMA) website, collecting the ten years preceding the date of the case study (period 2009/8 - 2019/8). Of particular interest were the data relating to average temperatures, relative humidity, precipitation, lighting, and cloudiness.

'Figure 21' (on the next page) graphically displays the average maximum and minimum monthly temperatures and the comfort temperature (based on the equations described in the next chapter). During the period of the case study, cold season in November and December, the comfort temperatures are 21.0 °C and 18.2 °C, respectively, to reach the lowest in January with 16.9 °C (see 'figure 21').

Subsequently, the typical climatic data of the ventilation show the prevalence of winds from the south, however, during the months of interest, the direction turns to west and north-west (see figure 15) with weak winds but characterized by high peaks (the maximum average is recorded in October with 12.3 m/s). In particular, in 'figure 22' the vectorial averages of November and December are shown. Eventually, the amount of sunshine shows more considerable cloudiness in the period of November compared to December. As discussed in the next subsection, the boundary conditions affect the amount of time the sun enters the room.

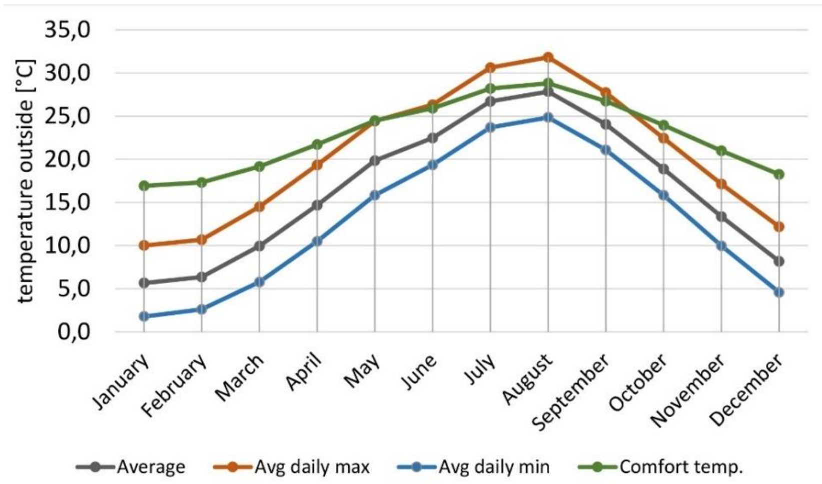


Figure 21. Typical average temperatures in Tokyo (the comfort temperatures are in green).

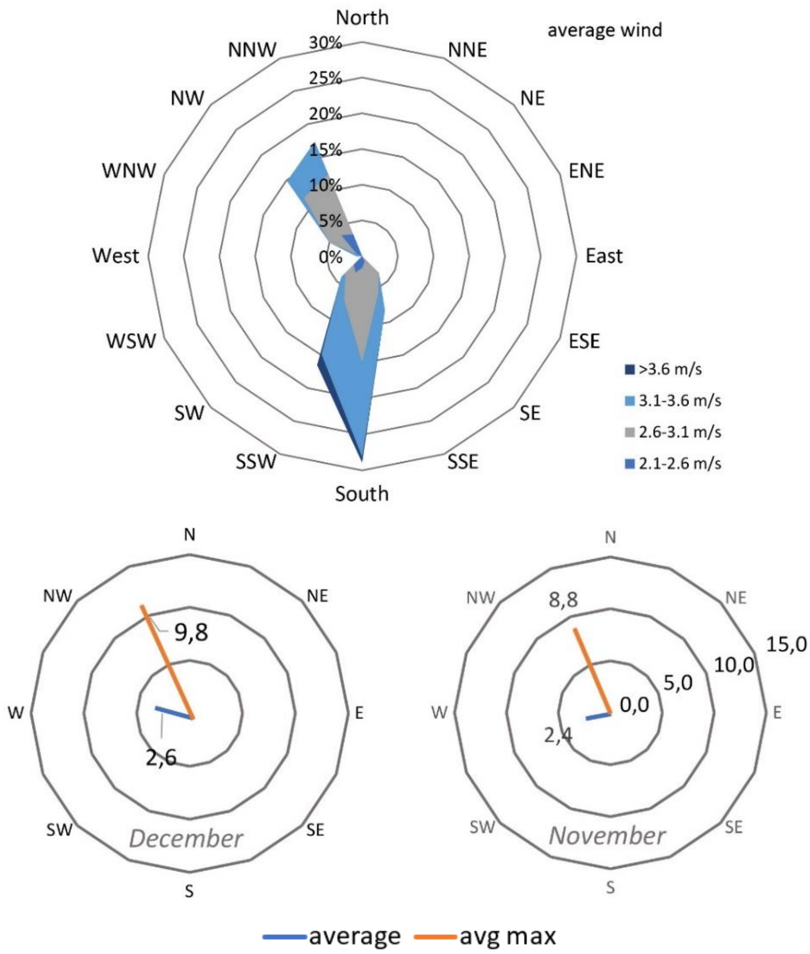


Figure 22. Features of prevalent wind during the year (above). Direction and average speed during the months of interest (below).

2.3.2. Microclimate analysis

The meeting room used for the test was on the fifth floor of a block of laboratories inside the Campus of The University of Tokyo (Komaba, Meguro-Ku). It was accessible from a North-South corridor that reaches the building facades, whose pivot-windows were operable by the users. On the long side of the room, there was a full-height curtain wall that faces an internal courtyard. Through an outward opening window-door, it was possible to enter a wide balcony. To this door, a parapet was added to obtain the shape of a typical window opening, which became the testing compartment for all the following activities in the field.

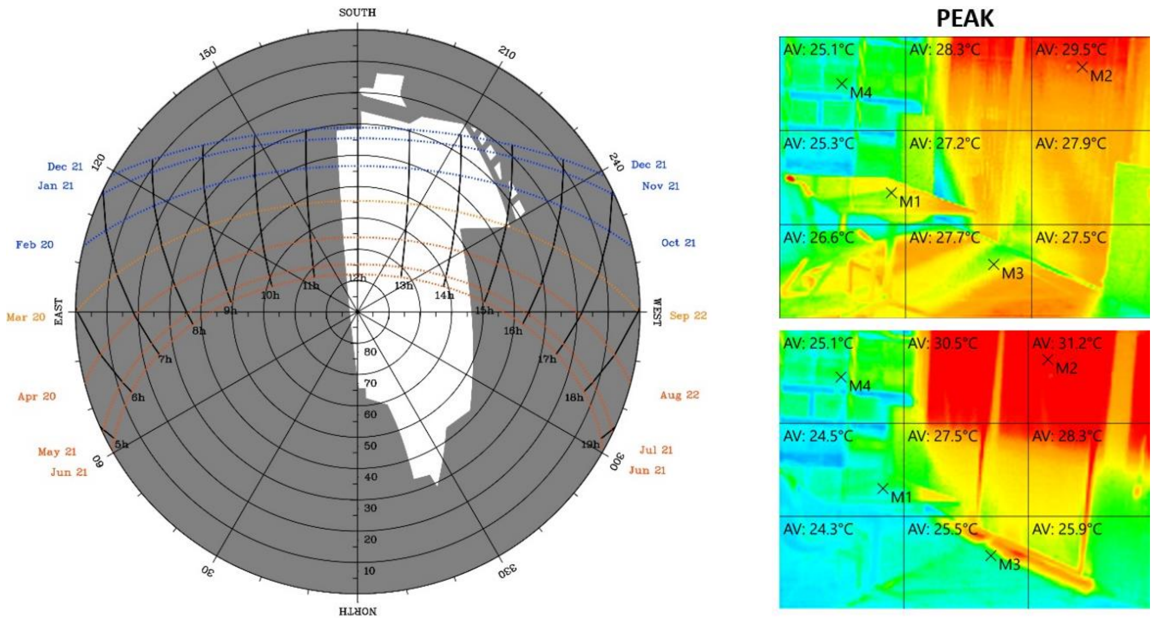


Figure 23. Sun path chart outside the test window (left), and thermal images of the window during sun radiation peak on a clear day in November (right).

In 'figure 23', the sun path chart with polar coordinates is superimposed with the projected shadows of the building immediately outside the window (obtained through a fish-eye camera). The image shows that the sun enters the room between 11:30 and 14:30. This time frame starts before and almost covers the entire duration of the meeting. The images on the right instead visualize the indoor radiating temperatures when the sun hits the curtain wall while it is protected by roll-up curtains (below) or not (above). In specific, it is shown the peak of the radiant temperature (31 °C) during the meeting period in the absence of cloud cover. 'Figure 24' illustrates the same image evidencing the variation of sunshine conditions over time.

This first analysis helped to define the current microclimate conditions faced by the user during the meeting and to decide how to alter indoor parameters according to the given conditions. Afterward, I followed studying the ventilation aspects.

Figure 24. Time sequence illustrating solar radiation inside the meeting room with open curtains.

The context made it difficult to interpret the general data on ventilation, for the fact that the window was protected on all sides. Nevertheless, I conducted a smoke test divided into two sessions (calm and windy day) to have a more precise indication on the path of internal ventilation in single-sided and cross ventilation situations (see ‘figure 25’). Notably, 4+4 video sessions were carried out and analyzed to assess the maximum intensity and direction of the internal flow.

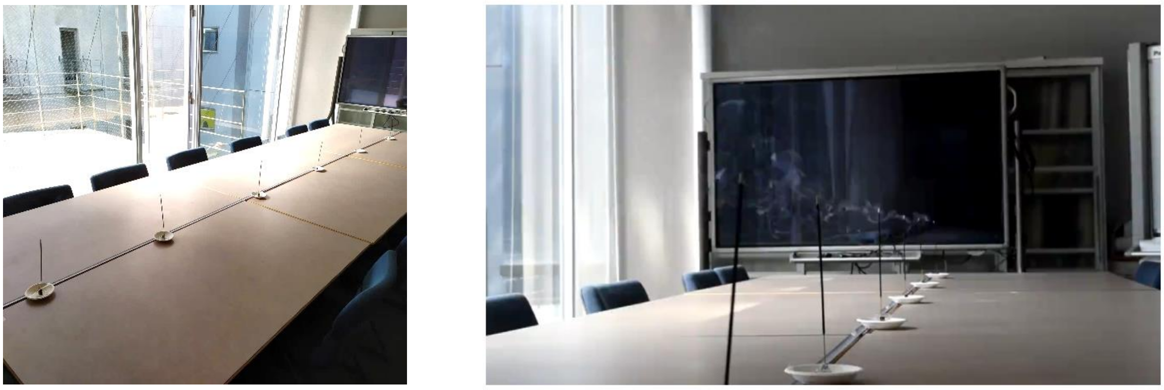


Figure 25. The layout of the smoke test inside the meeting room (left, a screenshot from the video recordings)

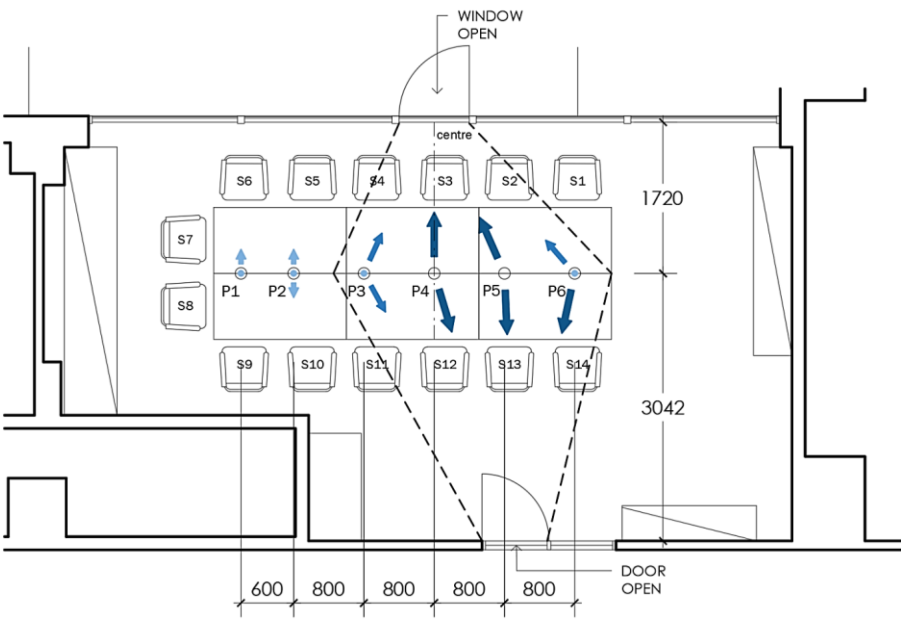


Figure 26. Results of the video analysis of the smoke tests during a windy day.

The smoke experiment revealed how the middle seats of the table are the most subjected to natural ventilation (see 'figure 26'). It also indicated the bidirectionality of the flow during cross-ventilation conditions. Finally, I repeated the experiment with the use of four anemometers, one in front of the opened window and the other three on the table at 15 cm high. The data confirmed the outcomes of the smoke tests.

2.3.3. Environmental monitoring method

Four different measurement tools were used to collect environmental data during the case study. The same tools were utilized in other tests described in this thesis (see 'table 5' for general specifications).

In the case of the internal and surface temperatures, it was adopted a 93-channel model 9350A CADAC3 Multi-System Logger, which was connected to type T thermocouples. The reason to use this type of thermocouple is that they are accurate with excellent stability and repeatability. Furthermore, they are practical, given that they can be used to detect both surface temperatures and air temperatures. However, during the case study, I adopted other devices for the air temperature. Specifically, for the measurement of indoor air temperature, relative humidity, and internal CO_2 concentration, I used the TANDD RTR-576 Data Logger, which is equipped with three channels. It has an integrated Non-Dispersive Infrared (NDIR) sensor and a probe containing a thermistor and a polymer resistor for measuring temperature and relative humidity.

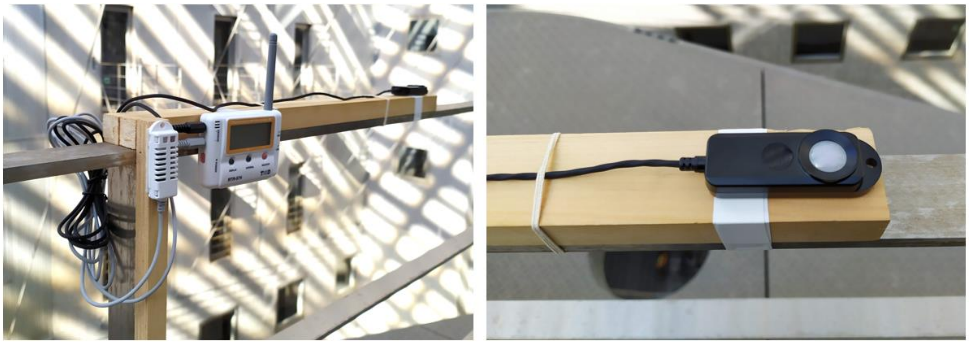


Figure 27. The small monitoring station installed right outside the testing room (left) and a detail of the radiation probe (right).

Subsequently, outside the testing room, a small monitoring station was installed using the 4-channel TANDD RTR-574 Data Logger receiving two probes. The first is identical to the one connected to the RTR-576, and the other is a UV and illuminance photoresistor (see 'figure 27').

Finally, four probes TESTO 405i hot-wire anemometers were used to measure the air velocity. The technology consists of the use of a heated metal wire (e.g., platinum), which exposed to air, provides a resistance value based on temperature fluctuations due to the wind speed. As discussed in the next subsection, these probes are extremely sensitive but have a problem related to directionality. After the collection of all the sensing instruments, I calibrated and carefully positioned them inside the testing room to guarantee the measurement quality.

Table 5. Model and specifications of the sensors and probes utilized for the test.

Model	Parameter	Accuracy	Data res.	Range	Time res.
CADAC3 9350 A	Temperature	± 0.05% + 0.3 °C (0-150 °C)	0.1 °C	-270 to 370 °C	from 60 Hz
TANDD RTR-574	Illuminance UV intensity Temperature Humidity	Illum: 10 lx to 100 klx UV: 0.1 to 30 mW/cm2 Temp: ±0.5 °C RH: ±5 %	0.01 lx 10^{-3} mW/cm^2 0.1 °C 1 %	0 lx to 130 klx 0 to 30 mW/ 0 to 55 °C 10 to 95 %	1 to 60 seconds
TANDD RTR-576	CO_2 Temperature Humidity	CO_2: ±(50 ppm + 5 %) Temp: ±0.5 °C RH: ±5 %	1 ppm 0.1 °C 1 %	0 to 9999 ppm 0 to 55 °C 10 to 95 %	1 to 60 seconds
TESTO 405i	Wind velocity	±(0.1 m/s + 5 %)	0,01 m/s	0 - 30 m/s	2 seconds

2.3.4. Calibration and preparation of sensors

Different approaches were adopted to assess the accuracy of the monitoring stations. The manufacturer certified the reliability of the RTR-576 and 574 sensors. However, I compared the temperature and CO_2 readings with other devices such as analog thermometers and digital sensors. For humidity, I inserted the probes in a 62% RH test kit (see 'figure 28') and compared the data with the readings of a digital sensor. As a result, it was noticed a general accuracy of the probe (59% is inside the range ±0.5%).

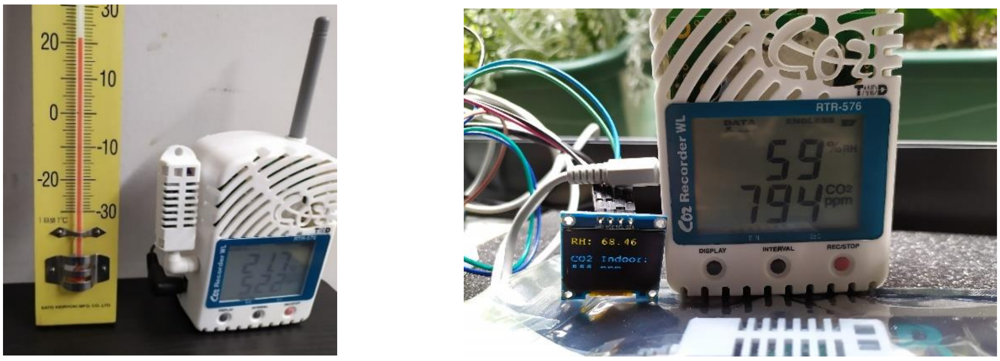


Figure 28. Further calibration of temperature readings comparing with an analog thermometer (left), and parallel readings of two humidity sensors inside an RH test kit at 62% (right).

To test the thermocouples, they were immersed in a mixture of water and ice, and the readings were confirmed through the Multi-System Logger connected to a PC. In ‘figure 29’ on the right side, it is shown the real-time temperatures detected by the seven wires, which reached temperatures around the zero as expected (channel 1 was disconnected).

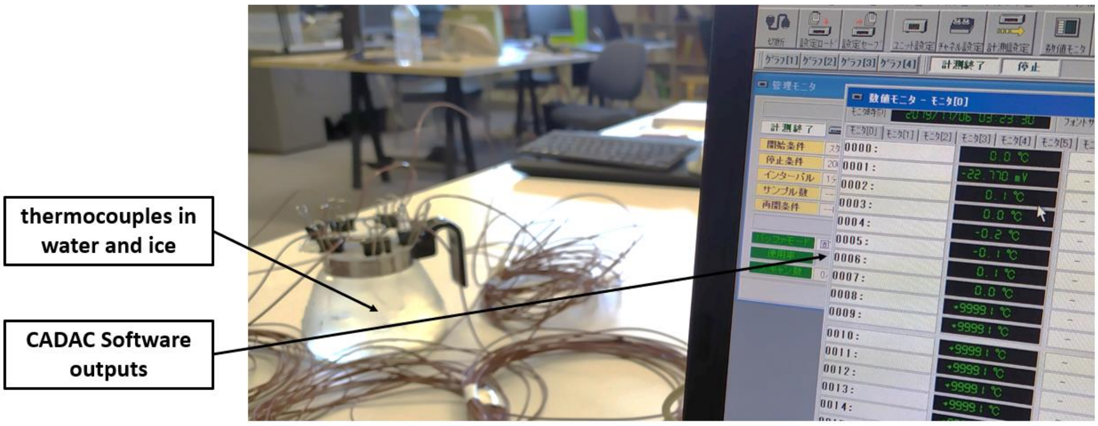
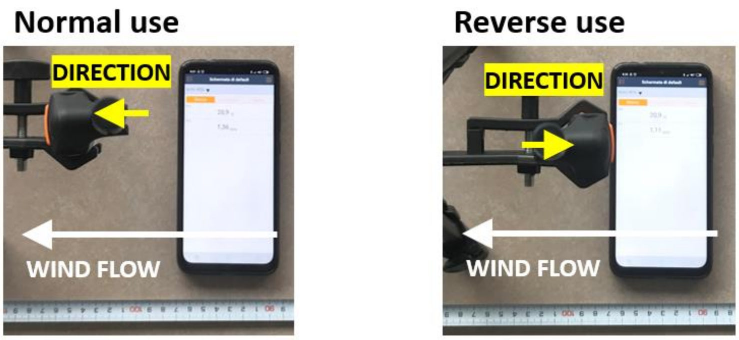


Figure 29. Calibration at 0° of Type T thermocouples in a solution of water and ice.

For the anemometers (also certified by the manufacturer), I wanted to test the sensitivity related to directionality, already reported by [49, 50]. I measured the readings in real-time, gradually moving away from a desk fan and using the probe in the correct and reversed position. The results showed evident reading difficulties, especially at low speeds, which are recurrent in indoor natural ventilation (see ‘figure 30’).



distance	[m/s] min	[m/s] max
100 cm	1.36	1.44
200 cm	0.44	0.76
400 cm	0.22	0.42

distance	[m/s] min	[m/s] max
100 cm	1.11	1.41
200 cm	0.43	0.73
400 cm	**0.03**	**0.10**

Figure 30. Testing the directionality of the anemometers. The tables show the measurements of different probe directions under a constant wind.

To overcome this problem, H Pabiou et al. (2015) proposed the addition of sensors consisting of thermocouples connected to a heater at the entrance of cylindrical tubes [49]. In this way, the sign of the pressure difference determines the direction of flow. Nevertheless, even though the solution indicated was interesting, it turned out to be not very practical for my purposes. Consequently, this uncertainty in the measurements was considered during field tests.

After the calibration, the sensors were placed in the room according to the scheme in 'figure 32' (on the next page). The RTR-576 was positioned one meter from the floor, referencing to the height of a seated person. Special attention was adopted in positioning it not too close to the table and the openings (about 1 meter). Eventually, the thermocouples were located far from windows and heat sources, placed as close as possible to the surface center, and insulated with polyurethane sponge and thermal adhesive (see 'figure 31').

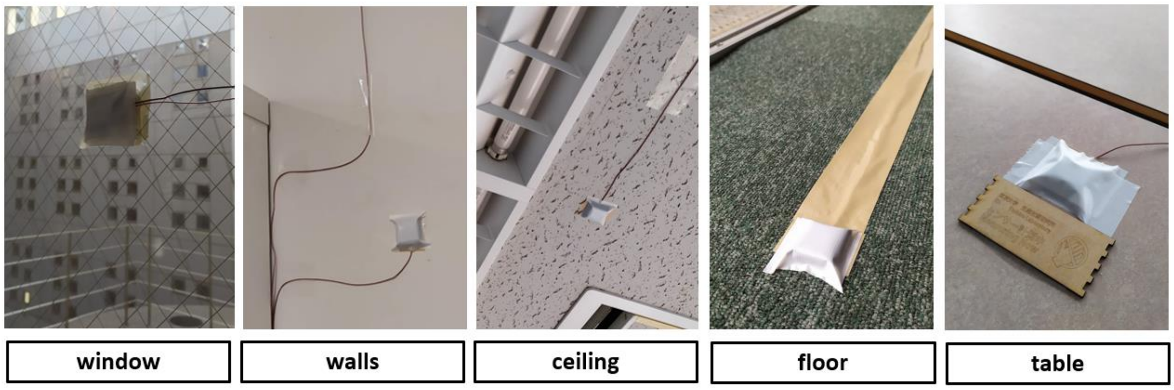


Figure 31. Positioning of the thermocouples inside the testing room.

2.3.5. Test procedures

Microclimate data were compared with the sensation and comfort votes of a group of people collected on three different days in November and December during a routine meeting from 13:00 until 15:00. Specifically, I collected external data (T_{out}, RH_{out}, Radiation, and lighting) internal data (CO_2, T_{ind}, RH_{ind}), and surface temperatures from the Data Logger. Additionally, all the units were synchronized to a 1-minute resolution.

Questionnaires were used to obtain information on comfort and sensations. Participants indicated the type of clothing (*clo*), their feelings and preference about the indoor environment, and, eventually, their comfort sensations. The questions were submitted after 15 minutes from the beginning (13:15), after an hour (14:00), and at the end of the meeting (15:00). Furthermore, people were asked to change positions according to the previous day to improve the randomness of the data.

The survey handed to the volunteers was based on the use of the 7-vote Bedford scale (-3 to +3) with a neutral state of comfort in zero [16]. Specifically, the questions referred to air temperature (general sensations) and surface temperature (localized sensations) and opinions about perceived air quality and humidity. Additionally, based on a study conducted by T Takahashi et al. (2000), I considered a variation to the response terms, more suitable for the positive/negative interpretation of the words from English to Japanese [51].

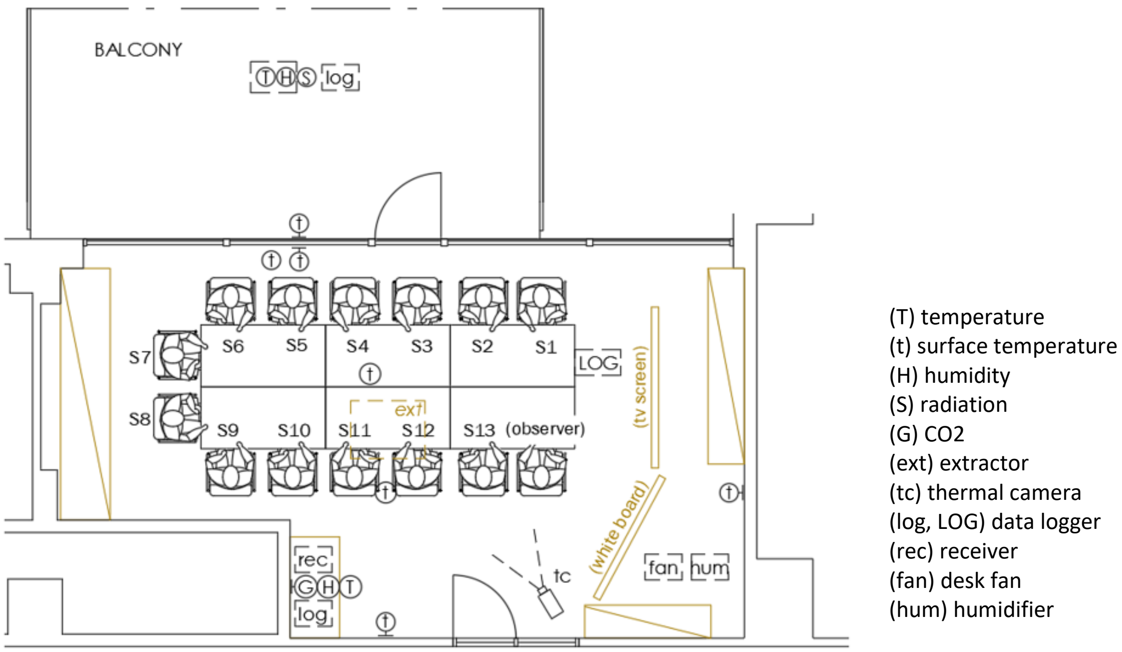


Figure 32. The layout of the meeting room for 'Case Study I.' The scheme indicates the position of the sensors, testers, and observer during the test.

In the survey, I also added questions related to the 'preference,' asking the testers how they would have changed the current situation for the better. The addition was based on Nicol's considerations that you cannot expect that people always consider neutrality the desired condition [20]. For further details, in 'Annex A,' there is the questionnaire sample used during the case study.

As the observer, I partially controlled the boundary conditions to increase the variation of the answers as much as possible. The test was conducted under FR mode (no use of HVAC system) and to vary the microclimatic parameters inside the room as much as possible, I managed the arrangement of the door and window, curtains, and used the air extractor and a humidifier (see 'figure 32'). Particularly, the latter was accompanied by a fan to better diffuse humid air and was hidden from the sight not to influence the votes.

‘Figure 33’ illustrates the variations of boundary conditions during the three steps of the questionnaire (*q1*, *q2*, *q3* vertically) and on different days (*c1*, *c2*, *c3* horizontally). I focused on conducting them without interfering with the meeting sessions. Individually, the first day the curtains were down, and the humidifier was turned on during the meeting. The second day I turned on the extractor and the humidifier from the beginning. Then, the third day I only used the extractor, and the curtains were always down. The door and window opening helped in CO_2 and temperature management. Additionally, the curtain wall was sealed with thermal adhesive to create an airtightness condition for better control of CO_2 concentration levels.

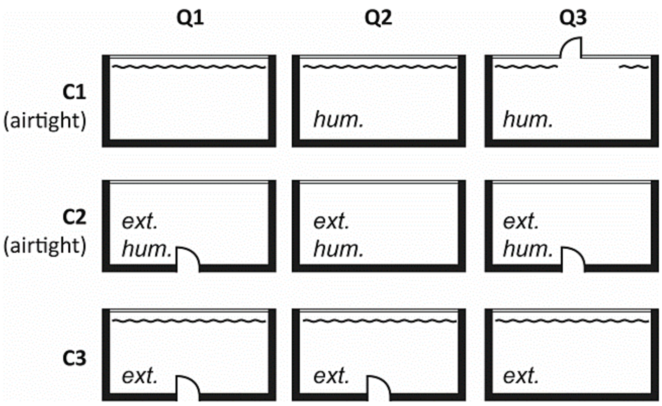


Figure 33. Variation of boundary conditions during ‘Case Study I.’ The air extractor (ext) and a humidifier (hum) were also utilized.

2.3.6. Results and discussion

In the following text, it is reported the results of the first case study and a discussion on the volunteers' reactions to climate variations during the meeting sessions.

The size of the data sample was relatively small for making precise inferences. Even if they were qualitatively assessed, the results helped to direct the research towards one direction. ‘Table 6’ shows a summary of the data collected and the minimum, maximum, and average values of the parameters experienced by the group of people. As indicated, thirteen subjects (ten males, three females) participated in the test, with an average age of 31 and *clo* levels of 1,3 (a little low for winter season). Specifically, clothes levels were calculated considering the database provided by E McCulough et al. (1984) [52]. Finally, the group expressed neutral to good comfort satisfaction during the case study.

Exterior and interior conditions varied extensively during the test. ‘Figure 34’ illustrates the variations of T_{out}, RH_{out}, and Sun radiation for each of the three sessions. The first day (*c1*) was unusually hot and with an ideal humidity range. It is indicated by the outdoor temperatures, which were among the highest and always around comfort levels. The second session (*c2*) saw a sharp drop in outdoor temperatures (the lowest recorded) also due to the absence of sunshine. Finally, the third day (*c3*) was slightly warm but with relatively low humidity.

Table 6. Description of the collected data from 'Case Study I.'

Variable (T)	*N*	*Minimum*	*Maximum*	*Mean*	*Std. Deviation*
Indoor operative temp °C	400	18,8	25,3	22,0	2,08
Indoor air temp °C	427	18,3	25,5	22,3	1,95
Indoor Relative Humidity %	427	33%	56%	47%	7%
CO_2 Concentration (ppm)	427	518,0	2847,0	1283,0	545,33
Outdoor air temp °C	427	10,0	27,7	17,0	5,30
Outdoor Relative Humidity %	427	26%	69%	48%	17%
Sun radiation (mW/cm^2)	424	0,0	0,6	0,1	0,10
Outdoor illumination (lx)	424	1365	57950	6561	10610
Thermal Sensation Votes	109	-3,0	2,0	-0,2	0,86
RH Sensation Votes	109	-2,0	2,0	0,0	0,81
AQ Sensation Votes	109	-2,0	2,0	0,1	0,96
Thermal Preference Votes	108	-2,0	2,0	0,1	0,71
RH Preference Votes	108	-1,0	1,0	0,1	0,49
Temp Difference Preference Vote	108	-2,0	2,0	0,1	0,70
Actual Comfort Votes	101	2,0	6,0	4,1	2,09
Clothing insulation (clo)	34	0,9	1,62	1,3	0,34

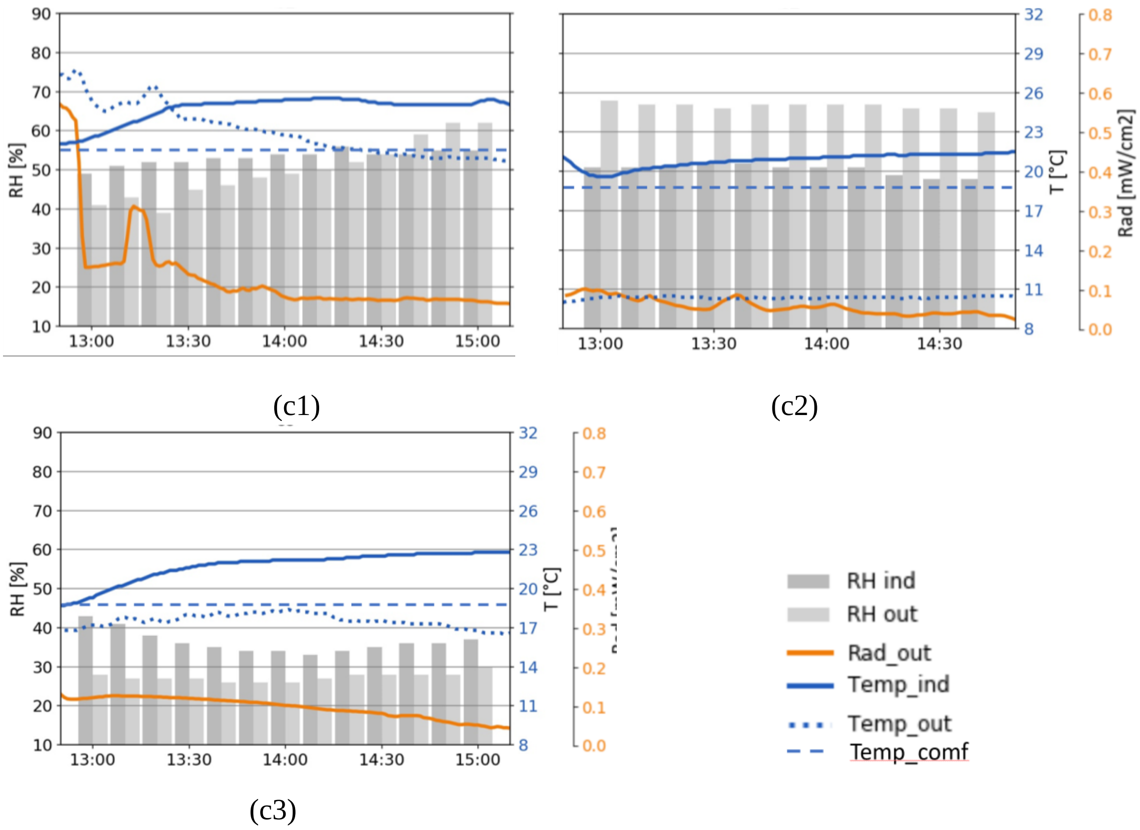


Figure 34. Data plots of the main environmental features of each recording session.

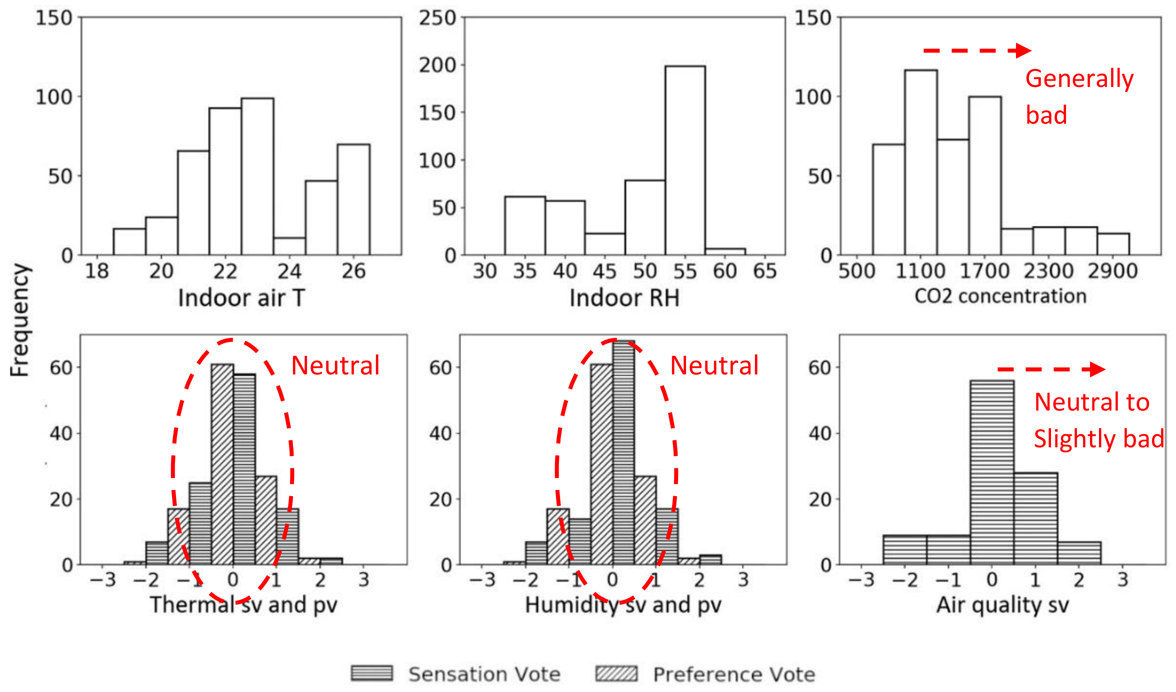


Figure 35. Frequency of environmental data compared with sensations and preference votes.

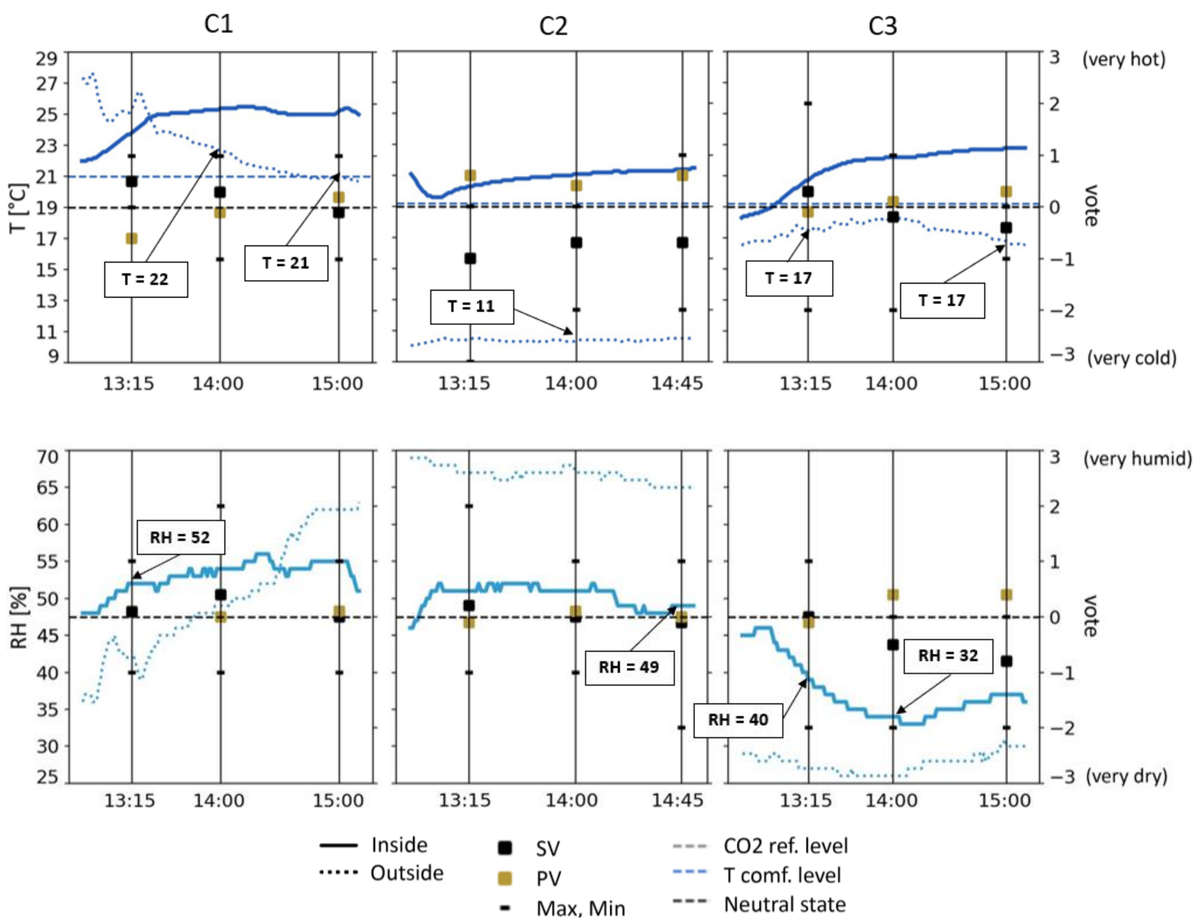


Figure 36. Line plots of Temperature and RH superimposed by sensation and preference votes for each session.

By observing the frequencies of the results of the three sessions, it was possible to define the overall comfort expressed by the group. In 'figure 35' (bar charts above), the data frequency of Indoor air temperature, indoor RH, and CO_2 concentration was compared with the frequency of the Sensation Votes (SV) and Preference Vote (PV) (bar charts below). While the parameters and sensations relating to humidity and temperature were considered neutral (tending to a normal distribution), the votes on air quality had a "slightly bad" response despite very high CO_2 values, which were almost always above the limit. It can be concluded that the group could recognize a specific bad condition of air, yet they had difficulty in identifying the "intensity" of the air quality problem. After this first analysis, I observed the correlation between indoor/outdoor climate conditions with people votes over time.

In each session, the differences in sensations and preferences votes depended on the environmental parameter of reference. The six boxplots in 'figure 36' show the trend over time of external and internal temperatures and RH (horizontally) compared to the sensation votes and preference votes during the various sessions (vertically). The position of the votes corresponds to the time when people filled the survey and are in line with the environmental time-series. Thus, I identified which boundary condition was experienced during each phase of the test.

According to the trends, the Thermal Sensation Votes (TSV) seemed to be influenced by outdoor temperature conditions, confirming the general adaptive principle indicating the relationship between users' feelings with external conditions. Meanwhile, sensation votes related to humidity levels tended to follow indoor fluctuations. Secondly, both votes referred to the single session, and the same environmental condition was judged differently according to the day. Concluding, the group identified the changes and indoor thermal tendencies in the short and long term.

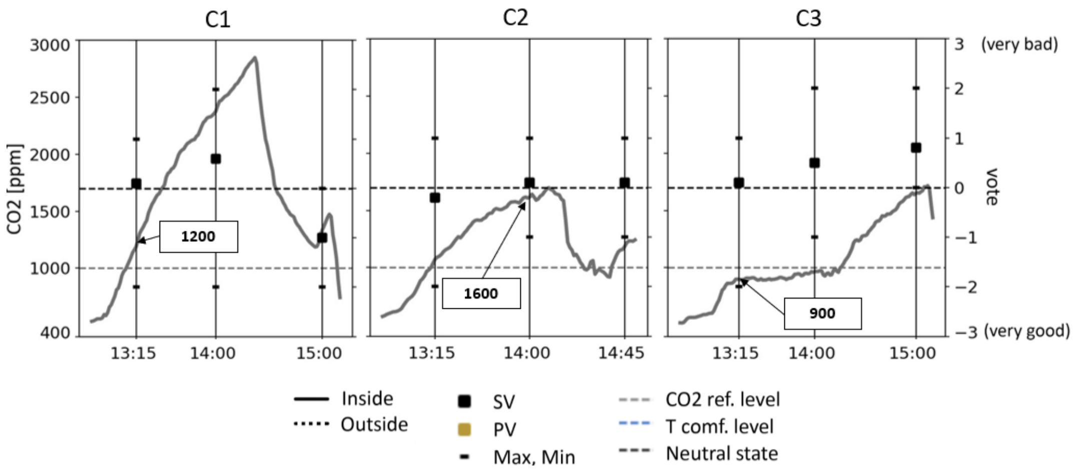


Figure 37. Boxplot of the variation of CO_2 concentration and sensation votes expressed over time.

On the other hand, the boxplot in ‘figure 37’ shows the relationship between CO_2 concentration and the SV referred to the air quality (the 1000 ppm limit is indicated as the reference limit for good air quality). The position of the SV and CO_2 concentrations followed each other in a trend of growth and decrease. Nevertheless, despite the general bad condition of the air, the votes had a neutral or just slightly negative value. Therefore, as anticipated by the frequency plots, there was an underestimation of the CO_2 levels, almost always above the limit, and a disagreement on the votes of individual people who mark a sharp distance between the maximum and minimum votes (even reaching 4 points of difference in *c1*).

As already observed in temperature and humidity perceptions, the votes are linked to the current condition, which was considered differently over a relatively long time. This aspect emphasized the centrality of user experience and adaptation to the environment and climate variations over the long term. Subsequently, turning the attention to the localized temperature difference perceived through the body, the average of the votes followed the trend of the surface temperatures.

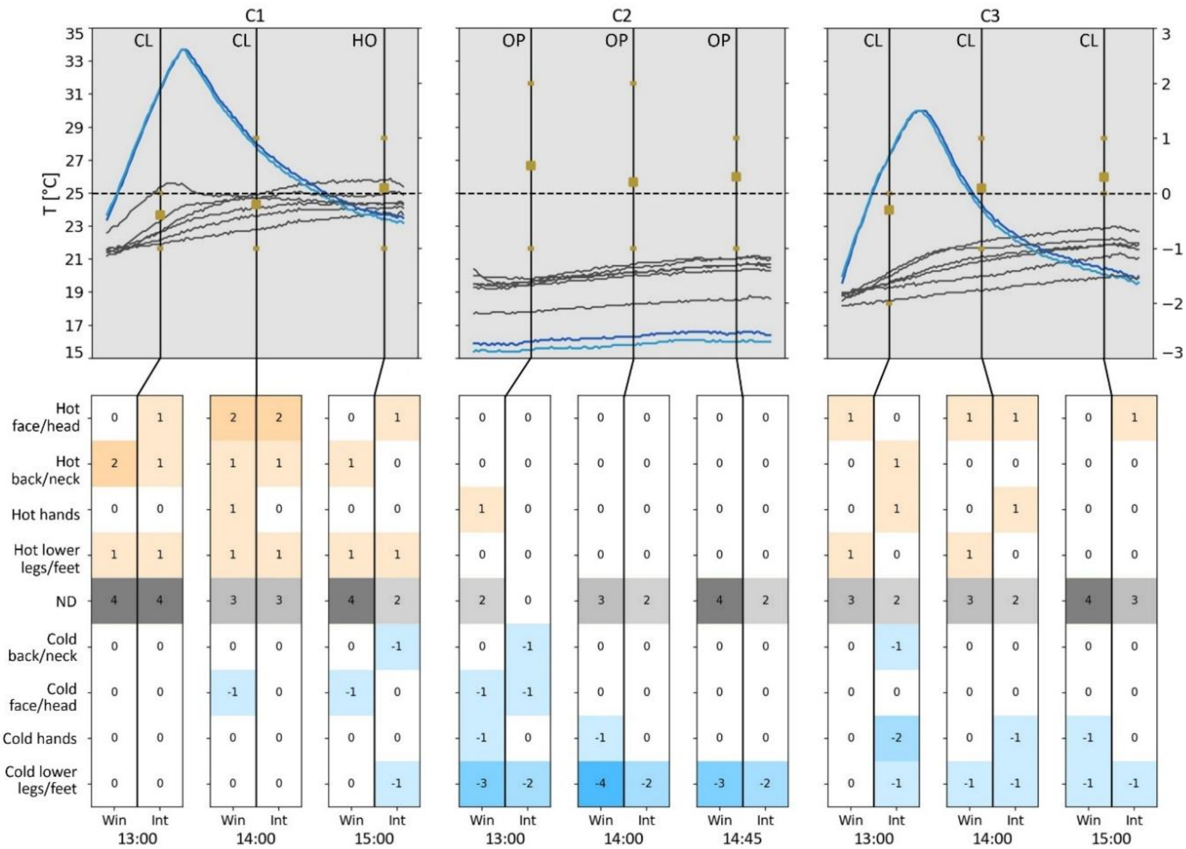


Figure 38. Line graphs of surface temperatures compared with preference votes (above), and localization of body thermal sensations during each question time (below).

In ‘figure 38’, the light and dark blue lines represent the outside and inside of the window, respectively, while the grey lines indicate the indoor temperatures of the other surfaces. Then, preference votes are plotted (in ochre) and superimposed on the graph. In the lower part, there is a detail of the SV divided by the frequency of response and localization of the body area.

From the results, it was inferred that the voters desired a slightly colder environment in *c1* and a bit warmer condition in the other two sessions. Particularly, in *c1*, there was a general agreement in the preference votes. Observing the SV, the temperature difference was recognized even with the curtains down. Then, in *c2*, cold surface temperatures were reflected in cold sensations all around the feet area. Finally, in the case of *c3*, more balanced temperature conditions yielded an equal spread of the thermal sensation of the voters.

Votes related to the comfort expressed a positive tendency in all the time series. The boxplot in ‘figure 39’ indicates the Actual Mean Vote (AMV) related to the overall comfort, as the last question of the survey. I deduced that there was not a clear relationship between the variation on sensations votes and personal comfort votes. Furthermore, there was also a significant disagreement among individuals, especially when the environmental conditions were changeable in a short time, as happened in *c3*. However, *c1* at 15:00 corresponded to the highest average of comfort vote when the outside temperatures reached a comfortable condition. This aspect demonstrated once again the capability of outdoor averages in predicting comfort.

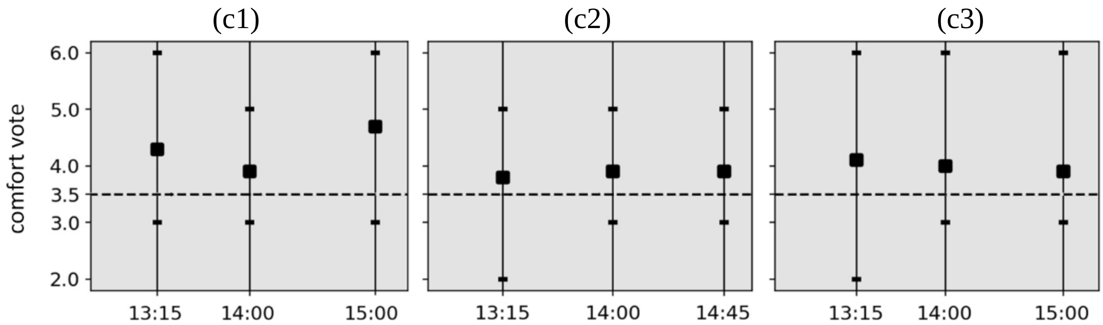


Figure 39. Actual comfort votes of the three sessions of ‘Case Study I.’

After a general analysis of the data, I calculated Pearson's R-squared and visualized the regression lines of the correlations between sensation votes and environmental parameters of the whole experiment (see ‘figure 40’). With scattered plots, I better identified the distribution of individual responses and saw their concentration based on the environmental variables. Although the results showed a low R-squared (probably because the sample was small), it was observed that the TSV and the outside air temperature had the highest correlation, which tendentially confirmed the link with outdoor air temperature. On the other hand, the relative humidity and the air quality showed more considerable disagreement among the subjects. In particular, the difference was quite remarkable between SV/Outdoor air T, which was less scattered and positive, and SV/CO_2, which turned to be more scattered and a very low 0,02 R^2.

Concluding, the purpose of the test was to assess the capabilities of a group of people in sensing climate changes around them. The case study generally confirmed that the analyzed sample had a higher capacity in recognizing temperature changes (both surface and outside air). Still, at the individual level, they had more difficulties in identifying CO_2 concentrations and RH.

Thanks to the case study, it was confirmed the importance of informing people about aspects that are difficult to perceive. Furthermore, it highlighted the centrality of a learning process capable of strengthening perceptions on factors hidden to human senses. In the following section, the text continues describing how people seek information within the environment and trigger an attitude towards learning.

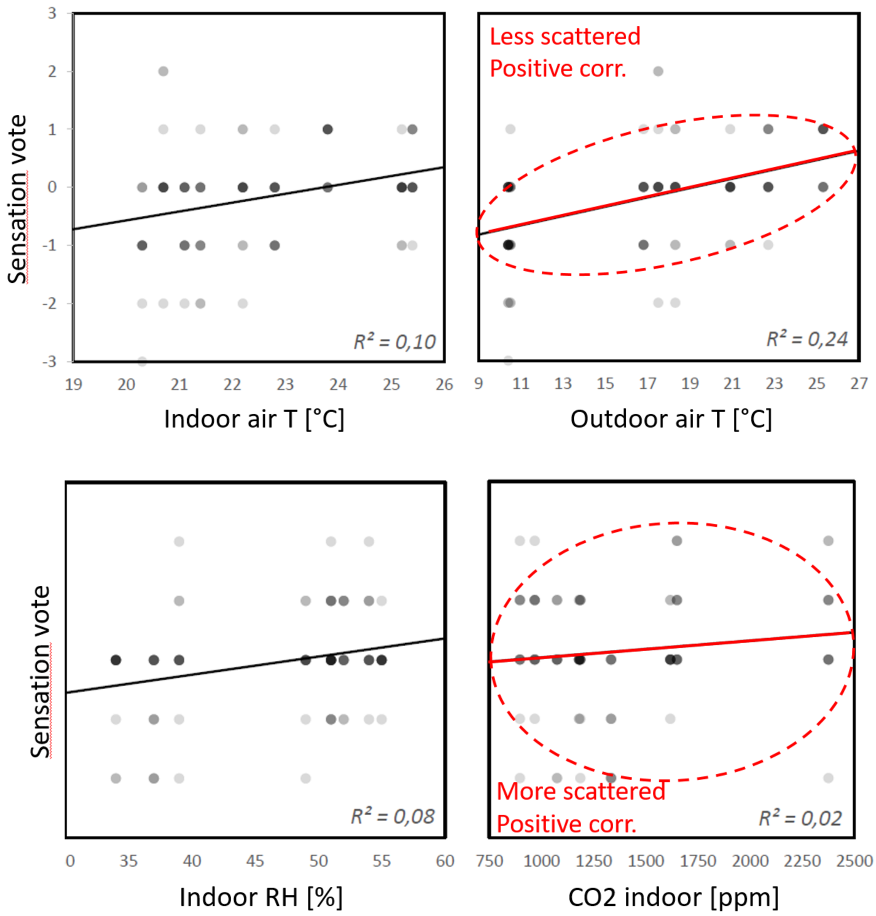


Figure 40. Correlation between sensation votes and environmental data.

2.4. Learning from the environment

Apart from the feelings and perceptions discussed previously, human beings receive constant information from their surroundings. This section considers that the built environment itself, with the help of sensing technologies, might promote learning paths in favor of comfort.

2.4.1. Learning-By-Doing to create new habits

Learning-By-Doing (LBD) was defined by B Bruce (2012) "(...) the process whereby people make sense of their experiences, especially those experiences in which they actively engage in making things and exploring the world" [53]. Regarding the definition, it is especially relevant to activities related to the exploration of the surrounding environment. LBD is considered the basis of many learning theories and is an approach adopted in adult education, management training, business [54]. Furthermore, it can be applied to everyday interaction with the built environment.

One of the things we acquire from LBD is experience. The more we accumulate it, the more expert we become in what we are doing [55]. More precisely, we learn by reflecting on experience. Furthermore, this learning experience is considered a cyclical process where knowledge is created through the direct involvement of users.

The learning experience can assist adaptation towards a change of habits and is linked to an active attitude. Specifically, learning includes the judgment of immediate existential experiences, foreseeing, and correct future actions.

It is natural to consider that reflection tends to inhibit action. However, as argued by D Kolb (2015), in creating a condition of creative adaptation, individuals naturally combine the concrete experience of interaction with abstraction, and experimentation with reflection, managing the conflict between these four adaptive modalities:

1. Concrete Experience (CE) or 'Feeling'
2. Reflective Observation (RO) or 'Watching'
3. Abstract Conceptualization (AC) or 'Thinking'
4. Active Experimentation (AE) or 'Doing'

Therefore, users can be not only active but also creative: they feel, think, observe, experiment.

In this perspective, the role of design and technology is taking advantage of the change of attitude of individuals to create new learning habits through the experience, and experiential learning can suggest a holistic approach to decision making. In fact, from the words of Kolb, “[it] is not a molecular educational concept but rather is a molar concept describing the central process of human adaptation to the social and physical environment.” [57]

In the meantime, the starting point of J Dewey's concept of experience was naturalistic, originating from an organism that adapts to their environment [54]. In his view, a learning cycle is triggered when a habit faces a disturbance, as considered in the adaptive theories. The thoughts and actions become a reconstructive and reflective process, making a distinction between a primary and secondary experience [54]. According to the scheme in ‘figure 41’, the process starts with discomfort. In ‘point 1’, something disturbs the regular habit that arises from the reasoning, creating a problem in ‘point 2’, where it is recognized and analyzed. Then, at ‘point 3’, there is an attempt to build a plan to control the situation, or ‘working hypothesis,’ which leads to reasoning (‘point 4’). Eventually, the hypothesis is finally tested in action at ‘point 5’, when the consequences of reasoning are probed in real practice. The end of the process is the resolution of the issue (primary experience), greater control in action, and also the creation of new ideas and meanings (secondary experience) [54]. In this approach, the role of technology is to clarify the working hypothesis and showing the means to solve a problem.

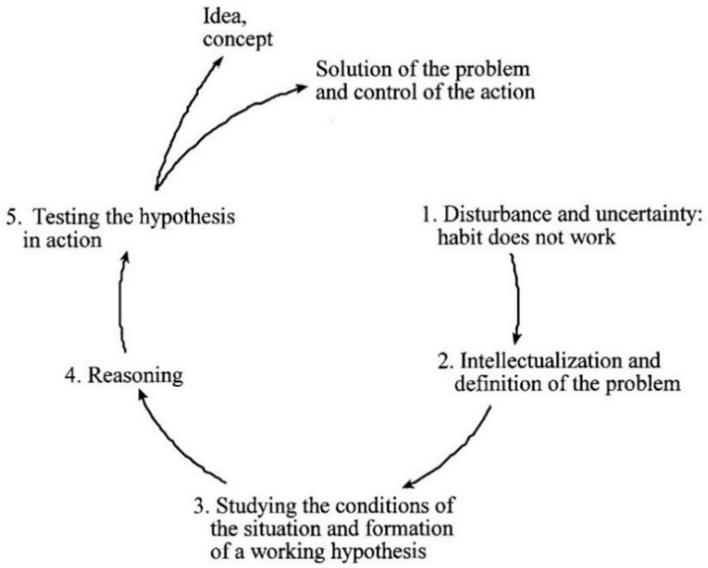


Figure 41. Learning-By-Doing as a cycle of thinking and action. *From Miettinen (2000).*

ICT systems could work starting from the second point showing unexpected issues not perceived by the person. Then, at ‘point 3’, they could suggest unperceived aspects of the environment that help to identify a new action scenario not considered previously. Subsequently, at ‘point 5’, they could provide provisional information to improve the operation. At the end of the process, they could make the idea formation more practical, showing the influence of the user’s decisions on the resulting data.

2.5. Literature review 1: Eco-feedback for learning processes

Stated the importance of ICT systems in learning processes, it was essential to define what kind of techniques are studied in the literature and how they could be implemented in systems dedicated to indoor comfort.

2.5.1. Feedback technologies to support decisions

The centrality of personal decisions brings researchers and professionals to design technologies capable of triggering a learning process. Different disciplines focus on the methods of communication through the use of feedback. Within construction systems, feedback is considered a way to learn from individual actions, from the actions of others, and a method to clarify users' intentions [56]. On the one hand, the same building can be considered passive feedback [12], or architecture as pedagogy, from the moment the building shows the designer's intentions and guides the actions of the occupants [56], for example through behaviors aimed at energy sufficiency. On the other, active technologies such as information displays are more explicit and point at guiding user decisions. Therefore, they could become a way of bridging the gap between one's actions and the results obtained [58].

In light of the above, this work mainly referred to design aspects linked to individual learning with the use of feedback systems. For more details on other kinds of influences within the process (like community and social groups), refer to the 'Annex D.'

Based on the definition given by the OED, S Darby (2006) defined feedback as the "information about the result of a process or action that can be used in modification or control of a process or system ... especially by noting the difference between a desired and an actual result "[59]. Therefore, it can be considered a mechanism that allows the user to make sense of the world around them. It generally refers to the reduction of energy consumption, or "making the energy consumption visible" [60]. However, over time the concept has expanded by incorporating other types of pro-environmental behavior aimed at sustainability [61].

2.5.2. Different types of feedback and previous reviews

Eco-feedback is widely analyzed within HCI studies, where sensitivity to climate change has led to the identification of persuasive mechanisms to increase sustainable behavior. More precisely, according to HCI, sustainability through design means "monitoring the state of the physical world; (...) and informing individuals' personal choices in consumption and behavior" [62]. Feedback or eco-feedback mechanisms can be categorized into two main types:

1. Direct feedback
2. Indirect feedback

The first type is aimed at informing the user directly, e.g., through displays. The second group is the information previously processed and addressed to the user [58], e.g., energy bills or auditing. This text is referred to the direct feedback, which mostly affects design aspects.

In a literature review, C DiSalvo et al. (2010) identified five different kinds of studies within the HCI involving direct feedbacks. 'Table 7' highlights three genres closely linked to the direct feedback mechanisms [62]. The author suggested that they are not exclusive and are often combined.

At the first point, there are persuasive techniques aimed at modifying or correcting behavior. Although they compare in most studies, ambient awareness technologies often overlap because many authors indicate that awareness can also trigger a change in behavior. Awareness technologies vary drastically from indoor/outdoor physical installations to interactive displays and energy meters. At the third point, pervasive and participatory technologies provide for the use of sensor networks to describe the environment around the user and allow a change in behavior [62].

Table 7. Feedback mechanism from different HCI studies.

Genres	Technological solution
1. Persuasive	An interactive technology attempting to convince users to behave or act in a particular (sustainable) way
2. Ambient awareness	Calm computing to construct systems that make people aware of some aspects of their environment
3. Pervasive and participatory	Based on sensing networks to detect contextual issues. Most of the time users collect data that potentially impacts their behavior (ex. citizen scientists or community environment information)

Finally, in another literature review, S Agnisarman et al. (2017) investigated persuasive technologies more extensively, with the analysis of 38 articles. The authors reconfirmed the high number of studies related to saving electricity (more than 60%). In specific, the followings are the main critical points highlighted by the authors [60]:

- These technologies are based on the designer's interpretation and on the fact that they will be able to direct behavior. However, the best practice is to customize the feedback depending on the type of user and his goals;
- The system is not a guarantee that the change of behavior lasts for a long time;

- The user's intellectual work should remain low, so an easy to understand interface can increase participation.

In the next text, the literature review is reported, and the various technologies are discussed from the point of view of the experiential learning process.

2.5.3. Development of the literature review

The scope of the literature review was explaining how feedback technologies integrated into design tools, could impact the behavior of people. The keywords used were "behavior change" AND "eco-feedback" within the ACM Digital Library between 2013-2018. Two papers were added to the list, one relating to indoor air quality, and another to HVAC systems. A total of 23 technologies were analyzed, following the categorization indicated by DiSalvo et al.

After the paper collection and analysis, the next step was highlighting the learning processes induced by each genre of feedback. Mainly, different strategies were found such as learning by observing (13 papers), discussing inside the group (5 papers), sharing results in social media (4 papers), contemplating physical installation (3 papers), comparing personal behavior (3 papers), goal achievements (3 papers), playing (1 paper) and interacting (3 papers).

Finally, I identified the type of target (individual or social) and the purpose of the design. The latter is generally to inform behavior concerning electricity, but also to reduce water consumption, greenhouse gas emissions, or a general change in the lifestyle, and better management in monitoring sensor networks (see ‘table 8’ at the end of the section). In the following text, it is described in detail the different learning techniques based on the solutions found in the literature.

2.5.4. Learning from persuasive technologies

Persuasive mechanisms fully involve the user in a behavioral change according to the objectives declared by the designer. This process is often connected to the achievement of a goal, to the comparison of personal results, to sharing information aimed at generating healthy competition with users on the net or within the family.

In this group, the solutions based on the observation of data from digital displays or web platforms (symbols, graphs, or values) were numerous (e.g., in [63, 64, 65, 66, 67]). In the paper by L Piccolo et al. (2018), 150 households in the UK were supplied with smart sockets and digital displays for showing energy consumption. The information, which became more accessible, was designed to generate a change in attitude in energy consumption [63].

Furthermore, the combination with social media allowed a greater diffusion of technology and data sharing, promoting an exchange of information between the families involved. At the same time, there were papers describing achievement learning mechanisms [64, 68, 69]. In the article by P Inym et al. (2018), an application based on three levels of involvement was developed. It ranged from the first level of general "perception," to a level of "understanding" with the use of feedback, up to the "projection" through the creation of personal goals [64].

Persuasive mechanisms can generate learning processes through self-comparison and sharing within a group of people (e.g., in [63, 64, 70]). Y Laurllau et al. (2016) described a system based on an interactive calendar, which placed next to the shower, informed the family of water consumption habits, to strengthens personal comparison and shared learning [70]. Thus, the presence of such information had the potential to generate a change in collective behavior and the creation of roles within the group.

Other technologies were based on learning through interaction when using the system [64, 66, 70]. Always in the paper by Laurillau et al. (2016), among other technologies, they devised a LED lighting system that informed the user of the liters of water consumed in real-time, depending on the color of the light [70]. Subsequently, F Quintal et al. (2018), created a glowing socket that changed LED color according to the percentage of renewable energy available produced locally [66]. Therefore, at the time of plugging appliances, users could understand if the electricity they were going to consume came from fossil, hydroelectric, or solar energy.

2.5.5. Learning from awareness technologies

Compared to persuasive technologies, awareness-based solutions reduce the level of user involvement. They are aimed at raising the level of context awareness by giving the user more freedom in the decision-making. In this case, the learning process focuses more on observation, contemplation of physical displays, discussion within the group or socially, and involvement in serious games.

The observation of environmental data through digital/physical display is implemented to allow the users to be more aware of previously inaccessible information regarding their environment [63, 70, 71]. Particularly, S Kim & E Paulos (2010) experimented with the use of an air quality meter (based on particulate matter), which placed inside the living spaces showed the graphs on the trend of pollution in real-time atmospheric [71]. The authors suggested how the knowledge of the trend values was reflected in a change of activity in favor of air changes, especially with the use of windows.

Awareness technologies also take advantage of the contemplation or interaction with physical installations within public or private spaces. Thus, it is possible to establish a dialogue between users and trigger reflections on environmental issues [63, 66, 71]. For example, in the article by T Liu et al. (2016), a network of technological devices with solar panels was placed in a campus outdoor space. In the study, the authors demonstrated how the installation increased energy-related thinking in the student community [71]. In another example illustrated by F Quntal et al. (2018), this time for residential buildings, illuminated panels showed in real-time the level of green energy production in a specific area (electricity production visualization). Eventually, the authors argued how family groups were more aware of the origin of the energy used during daily activities [66].

2.5.6. Learning from pervasive and participatory technologies

The pervasive mechanisms welcome a free interpretation and management of the data coming from the sensors scattered in the user's environment to favor the achievement of personal objectives [73, 74, 75]. Therefore, the learning mechanism is linked to data observation and comparison over time and between systems.

The personalization of the interface is an essential feature of these tools. In the article by N Castelli et al. (2017), a customizable web dashboard was proposed. The authors underlined how users, after the first use with the preconfigured settings, preferred to adjust the system with their information of interest [74]. Mainly it could be explained considering the necessity to synthesize multiple information. In another article, W Miller et al. (2017), the eco-feedbacks sent by the electricity companies were considered inadequate in the management of energy from photovoltaic systems. In this case, a digital display triggered learning by comparing graphs from different periods, or by the relationship with the neighbor's plant production [75].

Along with pervasive mechanisms, the participatory ones also focus on observation and comparison [76, 77]. The two similar articles by S Pahl et al. (2016) and M L Mauriello et al. (2017), investigated the use of smartphone apps that displayed thermal images to help users monitor the dispersion of energy inside their homes. However, as highlighted by the second, providing the user with the problem did not necessarily lead to a resolution. Solving the issue was also linked to the ability of the user and the uncertainty of data interpretation [77].

Finally, the paper of Y Zhao et al. (2013) described an HVAC system based on machine learning. The user actively inputted current acoustic and thermal comfort complaints into the system, which learned optimal personalized control [78]. Therefore, it was the algorithm that learned on behalf of the user, adapting energy savings to their preferences.

2.5.7. Discussion and conclusions

Persuasive mechanisms are directly linked to a change in behavior and are most effective when they are linked to achieving clear objectives. The success of these technologies is measured by the behavioral change proposed by the designer and is usually reflected in the measurements before and after the intervention.

However, one interesting aspect is to integrate persuasion systems into everyday objects, which allow reinforcing learning by interacting (or doing) and bringing feedback closer to the moment of action and immediately receiving the results of one's decisions. Furthermore, they are positioned in the place where the action takes place, and users do not need to search for information elsewhere (e.g., using smartphones), also contributing to the non-obsolescence of technology and to maintaining behavior over time. Subsequently, web platforms allow users to broaden the comparison of their behavior with others, as long as they have the same lifestyles.

In the meantime, awareness mechanisms are ideal for informing of aspects that do not require full involvement. Additionally, they are useful when integrated into displays or environmental signaling systems. In the examples analyzed, the simple presence of installations combined with people's curiosity could lead to informing the user of some aspects left in the background, providing for a possible change of decisions.

The management of feedback from sensors generates a lot of environmental data. Pervasive systems require the management of multiple information, which should be configurable according to user needs. This collection of information must be managed to inform the user, but too much information, or contradicting data, can negatively influence the user's performances [60]. Consequently, a dedicated technology should allow the personalization of the interface to increase the chances of achieving one's goal.

Visual comparison helps to interpret the information, and eco-feedback must be targeted to the needs of those who use it. The participatory mechanisms suggested that identifying a problem does not necessarily lead to the desired outcomes and that the system must yield a spectrum of solutions. Therefore, it is also necessary to provide the means to address the issue.

To conclude, the literature review indicated the tendency of sustainable HCI studies to focus on energy consumption and an object-oriented view. Nevertheless, for the thesis, it was essential to remember that the object ‘surrounds’ the user, providing a more user-centered perspective, and extending the objective to consider indoor comfort. Additionally, the studies highlighted multiple feedback modalities that variate according to the design intentions. The following section explains how they can be combined and used to trigger learning processes aimed at comfort in the built environment.

Author	Building Type	Object	Category: Persuasive	Category: Awareness	Category: Pervasive	Category: Participatory	Learning by: Observing	Learning by: Contemplating	Learning by: Comparing	Learning by: Sharing	Learning by: Achieving	Learning by: Discussing	Learning by: Playing	Learning by: Interacting	Target: Individual	Target: Group/Social	Designer's scope: Electricity	Designer's scope: Water	Designer's scope: Carbon	Designer's scope: Air quality	Designer's scope: Monitoring	Designer's scope: Comfort	Designer's scope: Lifestyle	Brief description	General lesson
P. Inyim, et al. (2018)	Residence	Smartphone App	●				●		●	●	●				●	●	●							The authors ideate an app to trace, share and set goals for energy consumption reduction	The software is divided into different levels of involvement, from general awareness to goal settings
T. Liu, et al. (2016)	Public Space	Physical/ Interactive Display		●				●				●			●	●							●	The authors propose a physical display in public space to trigger people thinking about ecology	The simple presence of displays might trigger virtuous behavior
X. Wang, et al. (2017)	Residence	Smartphone App	●								●	●				●	●							The authors point at informing collaboration among housemates via a reminder app	Feedback systems can trigger discussion inside community of people, households or housemates.
B. Glogovac, et al. (2016)	-	Web platform	●							●	●					●			●					The author describe a social app where you share ecological actions with local people	Social sharing and gamification might increase positive habits
S. Pahl, et al. (2016)	Residence	Smartphone App				●	●		●						●		●							The paper illustrates a thermal image app to make people visualize domestic energy flows	Visualizing unperceived energy flows might empower users in long-lasting adaptation
F. Quintal, et al. (2018)	Residence	Physical/Interactive Display		●			●	●							●		●							They ideate a system to show local real-time green energy production	Visualization techniques might trigger curiosity, psychological reaction helping behavioural change
	Residence	Smart socket	●											●										Connected to the tool above glowing sockets inform of the energy sustainability	Users action are linked to immediate feedback thanks to embedded technologies
Y. Laurillau, et al. (2016)	Residence	Digital display	●						●	●				●	●	●		●						It the use of ambient lights and a smart calendar to trace water consumption	Embedded elements could possibly increase long lasting behavior compared to app
	Residence	Digital display		●			●								●			●						A software that categorize water consumption by device helping to indicating possible wastes	-
C. Jennet, et al. (2016)	Public Space	Physical/ Interactive Display		●								●	●			●							●	The authors design a physical game questioning about energy saving habits	-

Table 8. List and details of the reviewed paper. *(continues on the next page)*

N. Castelli, et al. (2017)	Residence	Web dashboard			●		●		●						●		●				●			The paper describes a web dashboard to permit customized visualization of smart home data	When users decide which information to monitor potentially increases the adoptability of the tool
M. Mauriello, et al. (2017)	-	Smartphone App				●	●		●						●		●							Similar to S. Pahl et al., the study investigate the impact on behaviour of thermal images	The paper suggests that informing user is often not enough and not lead to problem solving
S. Mennicken, et al. (2016)	Residence	Digital display			●		●		●							●	●				●			The author propose a digital calendar as smart home interface to feedback automated activities	Showing the behavior of building system for a week it adds retrospective check
	University Campus	Web platform		●								●				●	●						●	The authors manage a social media to share experiences and discussions related to energy use	-
L. Piccolo, et al. (2018)	University Campus	Digital display Smart socket	●				●		●							●	●						●	Connected to the tool above the author collect energy data from displays and smart sockets	-
	University Campus	Physical/ Interactive Display		●				●				●				●	●						●	A public installation change properties due to sustainability discussions in a social space	-
X. Zhuang, et al. (2018)	Workplace	Digital display	●				●							●	●		●							The author discuss how health levels visualized by the thermostat can help saving energy	Feedback displayed where are needed shorten the time between learning and action
W. Miller, et al. (2017)	Residence	Digital display			●		●		●	●					●		●							The authors consider informing individual prosumers about generated energy from PV cells	Users need eco-feedback tailored to their goals
G. Ma, et al. (2017)	Residence	Web platform Energy meters		●			●		●						●		●							It compares the effects of weekly reminders of energy consumptions depending on user culture	An effective feedback solution must be based on an accurate user profile
Y. Zhao, et al. (2013)	Workplace	Digital display				●								●	●		●					●		The authors describe a HVAC system that learns from acoustic and thermal complaints of users	A system that learn from user feedback could optimize different comfort scenarios
S. Kim, & E. Paulos (2010)	Residence	Digital display Web platform		●			●								●	●				●				The authors discuss the effects of air quality (PM) visualization inside household groups	The system increase discussion about health issues and air change strategies with windows

2.6. *Eco-feedback to achieve comfort goals*

This section indicates how different feedback mechanisms can address various users' attitudes within the building context. Then, a general framework illustrates their application in the Learning-By-Doing process towards comfort goals.

2.6.1. Levels of understanding inside the built environment

Feedback technologies within the built environment must consider the context. According to M Bates (2002), who focused on information seeking and its relations with anthropology and biology, people learn through different levels of understanding.

First, she affirmed that users immersed in their environment absorb 80% of information from awareness mechanisms. Bates defined this status as a combination of passive and undirected attitude and suggested that there are four different levels of understanding (see 'table 9'). Specifically, a directed/undirected attitude indicates whether the user is in search of particular information or not. Then, passive/active ones refer to user involvement, respectively, if he/she just absorbs or pays attention to the information [79]. In the meantime, while active and directed attitude brings to 'searching,' passive and directed ones describe a 'monitoring' level of understanding. Then, looking at the correlation between active and undirected attitude, it results in a 'browsing' mechanism. Finally, considering T Larsen (2010), it was possible to relate those levels to the feedback technologies previously discussed (see 'table 9') [80].

Table 9. Different levels of understanding and their relationship with feedback technologies. *Modified from Bates (2002) and Larsen (2010).*

	Active	**Passive**
Directed	Searching	Monitoring
Undirected	Browsing	Being Aware

	Active	**Passive**
Directed	Persuasive Participatory	Pervasive
Undirected	-	Awareness

The table suggests that each genre of feedback is indicated for a precise attitude inside the built environment. The next subsection defines the strategic timing and content to involve user attention towards comfort issues.

2.6.2. Timing and modalities to inform the process

Feedback mechanisms include not only the message but also the method of communicating it. The design dimensions of the feedback are 'information' (which relates to *what is* *communicated*?); 'timing' (which relates to *when is communicated*?) and 'display' (or *how is it communicated*?) [61]. Information is characterized by two aspects, such as granularity and message (or the actual content). Timing refers to the frequency, latency, and strategic timing. Finally, display refers to the mode of communication and its position in the space, as well as to the aspects of privacy and who can access the information (see 'figure 42').

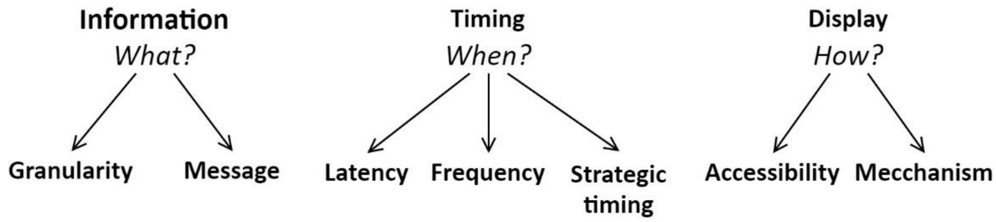


Figure 42. Design dimensions of feedback mechanisms.

In a process aimed at comfort goals, the first requirement is the use of a network of sensors that describes the environment that surrounds the user. Subsequently, the feedback is based on three strategic timings: the first is when the adaptation arises to solve a situation of discomfort that generates the evaluation of one's feelings. In this context, the ideal timing is to inform of the presence of a discomfort situation through mechanisms of ambient displays. The second is to communicate possible adaptive opportunities detailing different solutions in response to the discomfort signals. Finally, the third timing is the provision of detailed information during the adaptation and successive visualization of the results. In this case, the information is transmitted in real-time.

In 'figure 43,' the above mechanisms are applied to the LBD process. 'Step 1' indicates a disturbance concerning a particular moment in time, which is represented by a feeling of discomfort. Here the user defines the problem by evaluating his/her feelings ('step 2'). While the user is located far from the system, and its level of understanding is of general awareness, the feedback technology indicates possible causes of his/her malaise. The content of the message indicates the cause of the discomfort through a coarse granularity (for instance, using ambient displays). Additionally, the discomfort message could arrive before the user notices the disturbance.

In 'step 3', the user studies the current conditions and looks for adaptive opportunities. Here different solutions can be adopted, such as changing clothes, increasing metabolism, or acting to change the environment. In this step, the system communicates comfort opportunities by offering additional motivations to the user, requiring an intermediate level of granularity.

In ‘steps 4 and 5’, the user identifies a plan by weighing the various opportunities. At that time, he/she tests the plan in action, searching for detailed information that guides the achievement of the goal (e.g., inside a display). Eventually, the comfort goal is reached, and an idea is constructed by observing the result of the personal actions. The following diagram summarizes the Learning-By-Doing process towards a generic comfort goal.

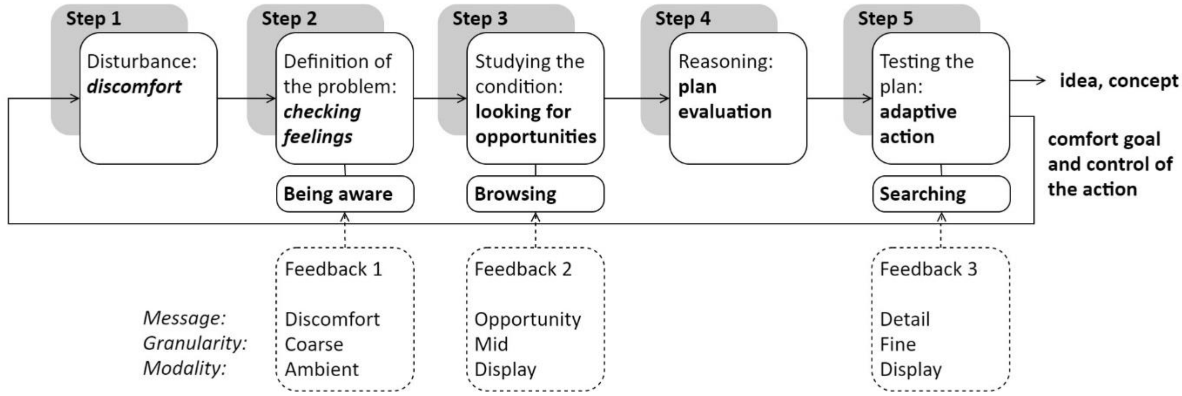


Figure 43. Feedback mechanisms towards comfort based on the main steps indicated by the Learning-By-Doing process.

In the next chapter, after understanding what the traditional drivers affecting human-window interaction are, it is discussed how to apply the above process to inform comfort achievement while operating windows.

CHAPTER III

LEARNING BY VENTILATING WINDOW SYSTEM

3.1. Introduction

This chapter takes the example of windows to describe Learning-By-Doing systems. It starts with a preliminary literature review on the drivers affecting human-window interaction, focusing on the learning aspects. Then, the second part introduces a concept for a window system. Specifically, it illustrates the main idea, its components, the communication system, and the User Interface. Afterward, the text continues presenting a framework of the Learning-By-Doing process towards comfort involving natural ventilation with windows. Eventually, the third part explains how people could learn from this novel system discussing comfort scenarios that fit different target profiles.

3.2. Studies on behavior with windows

The research aimed at describing Human Building Interaction (HBI) is essential in defining what the environmental and non-environmental factors that trigger adaptive opportunities are.

The activity carried out by the IEA Annex 66, which focused on defining and eventually simulating the behavior of occupants in buildings, indicated that the studies regarding windows are numerous [81], and extended for at least 25 years [82]. The overall process involves the collection of data (survey, monitoring), the definition and evaluation of statistical and probabilistic models, and the introduction of algorithms in BPS or BEMS, in the assessment of the energy impact, decision making, or to direct a change in behavior [81]. Besides, very often, the behavioral models are based on the principles of adaptive comfort, as in the case of the Humphreys algorithm, which used logistic regressions to correlate the indoor temperature with the window opening percentages [83].

Statistical studies certainly help to define the quantifiable aspects underlying human-window interaction. However, as can be expected, there are many non-environmental aspects (such as psychological, physiological, and social, among others) that influence or even constrain behavior.

Past reviews dedicated to the study of human behavior inside buildings helped to delineate the main aspects that explain human-window interaction. Specifically, V Fabi et al. (2012) summarized the categories of factors or 'driving forces' around the use of windows [84], and more recently, F Stazi et al. (2017) extended the review to include other devices (they also considers light switching, air conditioning, thermostat usage, fans, and doors) [82].

'Table 10' summarizes the categories indicated by Fabi et al., adding two other groups suggested by Stazi et al. A group lists time-related factors, because it is considered objective and recurrent in studies relating to windows, and the other called 'random factors' embraces unmeasurable aspects that can generate uncertainty [82].

The factors indicated by the authors are considered the first step towards adaptive behavior. These drivers lead to the perception of a stimulus, which subsequently translates into a scenario of integrated actions. Eventually, those affect both the individual and the surrounding environment. Therefore, depending on the decision made, user choices modify the quality of the internal environment, comfort, and consumption levels [84] (see 'figure 17' in 'section 1.9' as reference).

Table 10. Factors that influence behavior with windows. *Adapted from Fabi (2012) and Stazi (2017).*

Category	Description
Environmental factors	Directly affect the occupant (temperature, humidity, airspeed, noise, lighting, smells, et cetera)
Contextual factors	Indirectly affect actions such as building configuration (orientation, insulation, et cetera) and control devices (manual, programmable, et cetera)
Time-related factors	Repeated actions over a while (in the short term, in the week, seasonally and annually)
Psychological factors	Needs and expectations of the occupant towards the environment and the building, habit, lifestyle, and prior knowledge.
Physiological factors	Related to gender, age and health, activity level, clothing and food, and drink intake.
Social factors	Referred to the interaction with other people and users' roles within the group.
Random factors	Actions dependent on uncertain or non-quantifiable factors.

After analyzing the literature, Fabi et al. concluded that:

- The user applies two control modes to resolve discomfort, one given by bad air (air quality users), and the other by temperature (thermal comfort users);
- Outdoor temperature is the factor that mostly explains the probability of action;

- Psychological and physiological aspects are not investigated at the same level as the environmental ones, mainly due to the difficulty in measuring them;
- There is no general agreement regarding what is or is not the cause of behavior with windows;
- The drivers interact in a complex way and never individually, constituting a scenario of actions towards adaptation.

The authors also suggested that two common disagreements can be found within the literature. One is the different opinions between external or internal temperature in representing the best operation of the windows. The other is whether the concentration of CO_2 is a factor to consider.

First, it was recognized, for example, that outside temperature is influential even in winter and that it affects the occupant directly [85]. Instead, others suggested just using thermal comfort sensation as a trigger for window operation [86].

Second, as ‘Case Study I’ already suggested, aspects hardly recognizable by people such as RH and CO_2 are a matter of discussion. On the one hand, the CO_2 data is considered adequate to indicate the presence together with the PIR sensors (e.g., in [82]). On the same point of view, F Naspi (2018) argued that CO_2 is not an environmental driver since the presence of the person is needed to operate a window, which is why it has high statistical correlations [87]. In contrast, other authors recognized it as an aspect naturally linked to action (e.g., in [88, 89, 90]) or an index that negatively affects the opening [91]. Eventually, another article indicated that high correlations with CO_2 are more frequent in residential buildings [82].

3.3. Literature Review: traditional drivers in human-window interaction

The literature review updated Fabi's research to recent years and complemented the categories added by Stazi. Its focus was to define the main factors that commonly trigger human-window interaction, discussing them from the perspective of LBD. Then, to confirm whether the role of non-environmental factors was important within the process.

The method followed the collection of articles within *Science Direct* and *Springer*, regarding ‘occupant behavior,’ ‘interaction’ and ‘windows,’ in the period 2010-2019. Twenty-five articles were encountered that mainly consider the factors that influence the interaction (see ‘table 12’).

The papers were divided equally between commercial and residential studies (13 and 12, respectively). Looking at the metadata (see ‘figure 44’), the literature was grouped into common objectives:1) the study of the actions towards the window, 2) the study of the window position, 3) and the aspects relating to time. Eventually, the authors focused more on open/close action and window position throughout the day. In the following text, the results are described.

3.2.1. Primary and secondary drivers affecting the interaction

As identified by the other literature reviews, environmental factors were the drivers that have obtained the most correlations. In particular, the external temperature was considered in 24 papers between primary and secondary. Time-related factors came immediately after (see the figure below).

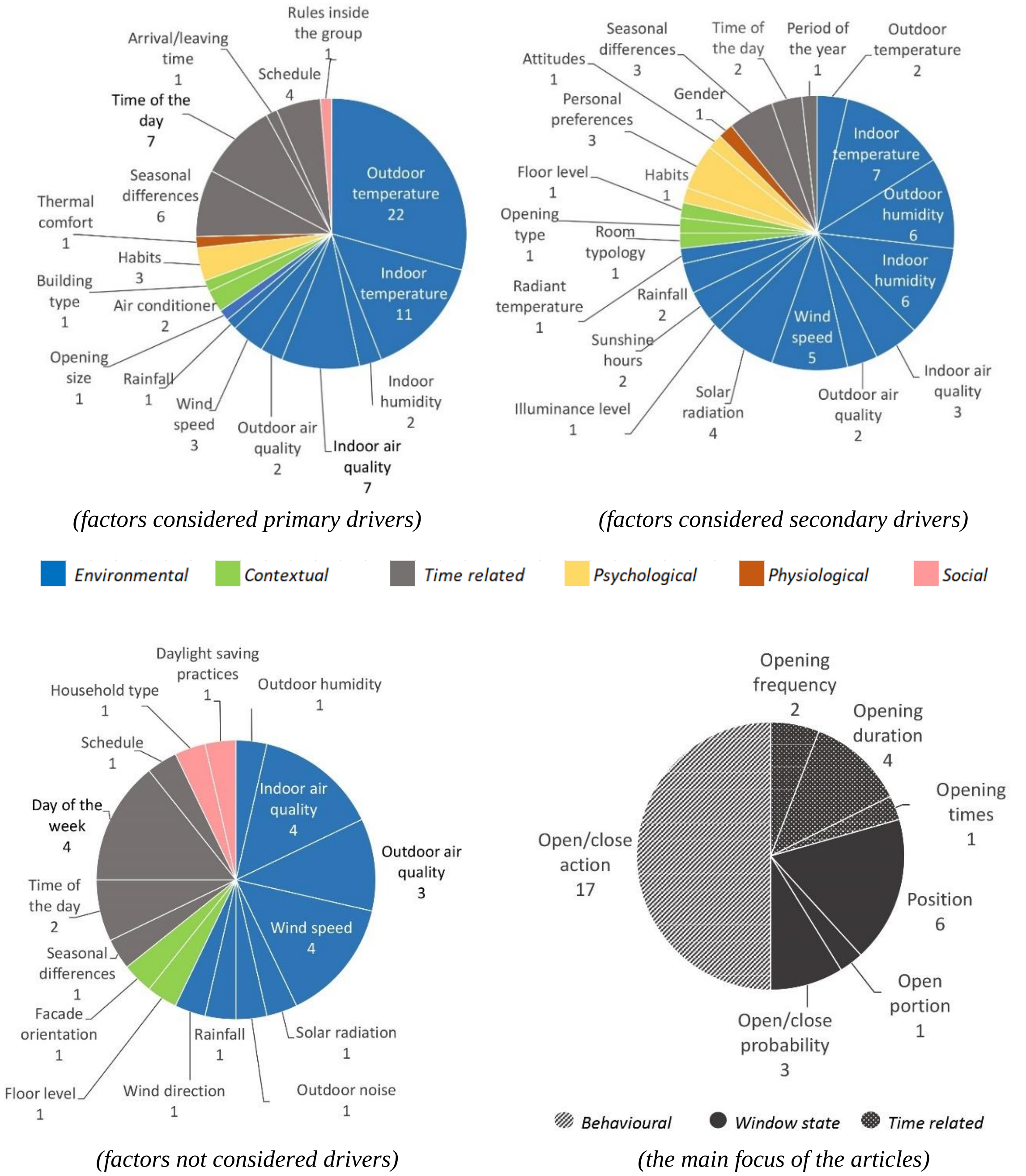


Figure 44. Frequency of the factors related to human-window interaction cited in the literature.

Although the occupant presence factor was mentioned in several articles, it was not listed because considered a precondition of the interaction [19]. Finally, among the non-drivers, many of them were recognized influencing factors by other authors, confirming a general disagreement within the research.

The complex nature of human-window interaction also leads to the use of more advanced forecasting methods. As the IEA Annex 66 study indicated, most of the articles used logistic regression methods, but there were also data mining approaches [92, 93]; and more complex stochastic models like Markov Chain [89, 94] and the ANN model [94]; the Bayesian Network [95], which is a graphic model for calculating irregular processes and serves to underline relationships between various factors and decisions with the probability distributions; the simulations with Monte Carlo model used for more random problems and related to psychological and subjective parameters [96]; the Gauss distribution [97] and the XGBoost algorithm [98] as alternative methods of modeling complex operations based on machine learning. Apart from the main drivers indicated in 'figure 44', the text down below details the principal observations and conclusions concerning the literature review.

3.2.2. Environmental factors

The increase in the probability of opening the window in line with external temperatures was found in many cases (e.g., in [94, 96]). D Lai et al. (2018), through a survey based on meteorological data, analyzed the behavior and habits of 14 families in major Chinese cities, in different climatic zones [88]. They suggested that the opening time of a window was proportional to the outside temperature up to a cut-off value and then decreases again. The same aspect was found in many other papers (e.g., [99-101]), and similar results were discussed by R Andersen et al. (2013) and D Calì et al. (2016). The latter emphasized how the increase in external temperature was negatively related to the probability of closing the window [89, 102]. F Naspi et al. (2018), in the analysis and discussion of offices in a Mediterranean climate, indicated how users interacted on arrival starting from 23 °C outside temperature, while in other regions, there are lower temperatures of reference [87].

The outdoor temperature also affects the opening hours, as indicated by X Zhou et al. (2018). The article described the concurrence of environmental and non-environmental factors in an open plan office in Nanjing [100]. In particular, the correlation between temperature and opening hours occurred in three different ways based on the period of the day. Finally, B Jeong et al. (2016), analyzing the data related to 20 apartments in Seoul, underlined that the drop in internal temperature was the most indicative parameter of closing windows compared to indoor temperature alone [103]. In addition, the opening frequency was more explainable with the lifestyle of the occupants and the daily activities, which varied depending on the time of year.

Other environmental aspects such as wind speed and relative humidity, the latter a more controversial factor, were found in numerous papers. As discussed by R Jones et al. (2017), in the investigation of 4 main bedrooms in the UK, the tester perceived discomfort when the humidity was outside the 30-70% range [104]. However, it was correlated with window opening also within those values. The authors attributed it to the perception of bad air quality as humidity increases, or to the fact that inside the tested rooms, there was a bathroom that could generate steam. At the same time, in the article by Y Wei et al. (2019), who investigated the use of windows inside 5 offices in Beijing, it was stated that the external humidity measured in a range from 10-70% could explain the increase in window opening together with the rise of wind speed (recorded between 0 and 3.2 m/s) [94].

Many of the studies in China dealt with the impact of the quality of the outside air in the use of windows. An analysis of 9 naturally ventilated apartments in Beijing by M Yao and B Zhao (2017), stressed that despite favorable environmental conditions, the $PM_{2.5}$ content of the air was reflected on the closing of the windows [105]. The same conclusion was indicated by S Pan et al. (2018), and from J Hou et al. (2017), who found that all the windows were closed at $PM_{2.5}$ values above 236 ug / m3 [99, 106]. Regarding the indoor air quality, Y Zhai et al. (2019), unlike other papers indicated by the authors, the perception of poor air quality did not deteriorate with increasing temperatures [107].

3.2.3. Non-environmental factors

Outside the environmental category, numerous non-environmental factors influence people's responses towards windows.

Fabi et al. considered that contextual factors influence interaction indirectly. As a matter of fact, in a study conducted by R Andersen et al. (2013), the authors analyzed 15 buildings of different types and ventilation methods in Copenhagen, identifying a change in attitude depending on the kind of residence [102]. While in the article of D Calì et al. (2016), who focused on the study of 60 apartments in southern Germany, it was detected a different interaction with openings depending on room function and the type of window (with parapet or balcony-door) [89]. This last aspect was also found by Z Shi et al. (2018) [108]. Finally, Y Jian et al. (2011), monitoring 5 residential buildings in Beijing, recognized four typical models adopted by families. They combined window adjustments with door operations, and the models changed by observing the bedrooms or the living room [109].

Other contextual aspects highlighted in the literature referred to orientation. Y Zhang and P Barrett (2012), in an investigation of numerous office rooms in a tall building in the city of Sheffield, discussed how the usability of a window is linked to sunshine, sun paths, and exposure to the prevalent winds [85].

Non-environmental aspects relating to time and schedule are particularly important in commercial buildings, such as the impact of use on arrival or departure (e.g., [87, 99, 110]). S Wei et al. (2013), who analyzed 36 individual office rooms in the UK, indicated the possibility to describe the position of the end-of-day window based on the departure time, but also on three different user attitudes, personal preferences, and general information [111]. Furthermore, M Yao and B Zhao (2017), monitored a large number of environmental and non-environmental aspects within 19 residential buildings in Beijing [91]. They concluded that the window opening is more common during the mornings and nights (as also identified in [95]), and is longer in summer than in winter (also in [112]).

Some authors identify the correlation between window interaction and seasonality. Z Shi et al. (2018) studied the use of natural ventilation inside two hospital departments in Nanjing, where patients were free to manage the windows according to their needs [108]. In this case, they indicated that the opening action was inversely proportional to the outside temperature during the summer seasons and directly proportional to the transition and winter seasons. High concentrations of internal humidity, on the other hand, made opening behavior more likely during the middle seasons, but not in the summer and winter seasons. Furthermore, C Sun et al. (2019) referred to seasonality in analyzing employee behavior inside 20 office buildings in Harbin, indicating how half of them left the window open continuously during the summer and, on the contrary, left them close the whole winter without taking into account environmental stimuli [92]. Finally, R Jones et al. (2017) suggested that seasonality affects the prevalence of one driver over another [104].

Social norms and habits can nullify the actions of users towards openings. Z Belafi et al. (2018), monitoring a school in Budapest, argued that the use of windows varied according to the classes because it was linked to different internal rules between students and teachers [110].

3.2.4. The impact of knowledge

In a large study conducted by S D’Oca et al. (2014), different methods of data analysis of 16 office rooms in Frankfurt were compared. Complex motivational patterns based on the combination of time and temperature, user attitude and routine, extent, and duration of window opening revealed correlations that could not be measured with traditional methods. Among other things, the authors highlighted that the users more interested in environmental aspects had a greater impact on internal ventilation [93]. Y Zhai et al. (2019) monitoring a study of architects and engineers in Alameda, concluded that the office users observed in the analysis had knowledge on natural ventilation, so they could effectively manage windows throughout the year, without using HVAC systems [107].

3.2.5. Discussion and conclusions

As discussed in the previous text, heterogeneous drivers contribute to the use of windows. As already suggested by Fabi et al., thermal and air quality control were the most discussed behaviors.

Regarding thermal aspects, outdoor temperatures can influence window operation according to a range of values, while the sudden drop of indoor temperature invites closing. Additionally, outdoor temperatures can affect opening hours. Therefore, such aspects might be better managed by a system with embedded technologies, which control such ranges over time.

For air quality behavior, there was no clear relation between indoor air status and window opening action. On the other hand, despite good outdoor conditions, outside pollution generally influenced window closing. These two facts confirmed that when users are aware of the presence of bad air quality, they commonly act to maintain healthy environments. From a design point of view, it suggested the use of feedback systems that invite users to open the window, considering the levels of indoor and outdoor air quality.

Among the non-environmental factors, time, knowledge, and the perception of control can influence the interaction with windows and indoor comfort.

First, window use was considered higher in summer than winter. This aspect might generate issues related to air change needs. Therefore, in a situation where the user is decoupled from the outside environment, a system dedicated to describing the outdoor climate could induce a short-time window opening. In this way, users would take advantage of favorable conditions even when they are not perceived.

Second, people interested in natural ventilation or knowledgeable in its mechanisms had more indoor impact and manage windows better compared to others. This aspect confirmed that feedback systems based on the learning process for natural ventilation might improve comfort in the long term.

Third, some authors indicated the direct benefits related to the control perception. G Brager et al. (2004) claimed that naturally ventilated offices increase environmental control and offer users the ability to search for temperatures experienced hours before. Besides, they benefit from the awareness of managing their well-being. Eventually, the authors stated that users express comfort from systems that have recognizable and controllable behavior [113]. As a result, designing a window interface that increases control perception through provisional information could indirectly affect the overall comfort sensations.

From a learning point of view, it was possible to distinguish the primary drivers into groups. ‘Table 11’ indicates three categories based on measurability and people perception:

1. Measurable factors, such as time, schedule, or temperature aspects;
2. Factors that are measurable but difficult to perceive by people (unsensed drivers), such as the concentration of CO_2, but also the perception of external events (especially with highly performing windows or use of HVAC);
3. Difficult to measure factors that refer to psychology, contextual aspects, the skill of the occupants, and users’ previous experiences.

Table 11. Groups of drivers considering the learning perspective.

Measurable factors	Schedule, arrival/leaving time, opening size, temperature (…)
Measurable but difficult to perceive	CO_2, Humidity indoor and outdoor, weather changes, air pollution outside, external events (…)
Factors difficult to measure	Contextual factors, psychology, skills, abilities, experience, habits, personal preferences, control perception, (…)

At ‘point 3’, the aspects related to user knowledge and ability are not directly measurable but of equal importance. For example, no one asks in the polls if people were able to control the situation or if their skills were enough for the purpose. These types of questions could increase designers' awareness of the efficacy of the built (and social) environment in easing window operations as a base for adaptive comfort strategies.

Concluding, HBI studies helped to highlight the traditional motivations that lead to window use. It stressed the importance of temperature and air quality variations as the primary motivation for window operation. However, in the collected articles, there was no suggestion on how design could improve adaptive opportunities with openings. Therefore, the implementation of design solutions was considered beneficial to academic discourse.

In light of the above, the next section describes the ideation of a window system dedicated to learning that insists on sensed/unsensed, measurable/unmeasurable factors to improve the user experience.

Author	Period of investigation	Building	Location	Method	Main drivers	Secondary drivers	Not considered drivers	Main scope	Notes
D. Lai et al. (2018)	12 months	58 apartments	Across China	Environmental sensors Opening sensors Meteorological data Survey	Outdoor temperature Seasonal differences Air conditioner Time of the day	Indoor temperature Indoor humidity Wind speed Radiant temperature	Household type Day of the week Seasonal differences	Opening duration Opening times	It indicates that opening time increases until a cut-off temperature outside
M. Yao, B. Zhao (2017)	12 months	19 residences	Beijing, China	Environmental sensors Opening sensors Survey	Outdoor temperature Seasonal differencess Time of the day	Indoor air quality Indoor temperature Indoor humidity Outdoor humidity Wind speed Wind direction	Day of the week	Opening duration Opening frequency	It indicates that in summer is more frequently open than winter, and that operation is just few times per day
R. Andersen et al. (2013)	8 months (no Autumn)	10 apartments 5 houses	Copenhagen, Denmark	Environmental sensors Survey	Building type Indoor air quality Outdoor temperature	Indoor humidity Outdoor humidity	Wind speed Outdoor air quality	Open/close probability	It suggests that outside temperture is more related with closing behavior
D. Calì et al. (2016)	48 months (36 of occupancy)	60 apartments (4 rooms in each)	Southern Germany	Environmental sensors Opening sensors Markov chain	Habits Time of the day Indoor air quality Outdoor temperature	Indoor temperature Outdoor temperature Outdoor humidity Room typology Opening type	Wind speed Floor level	Opening frequency Opening duration	It suggests that also room type and window type affect frequency of use
S. Pan et al. (2018)	9.5 months	5 offices	Beijing, China	Environmental sensors Opening sensors Survey	Outdoor temperature Indoor temperature	Wind speed Indoor humidity Outdoor air quality Solar radiation Sunshine hours Seasonal differences Time of the day Personal preferences	-	Open/close probability Position	It indicates different behavioral pattern related to window and comfort state during arrival or departure
S. Wei et al. (2013)	24 months	36 office rooms	UK	Environmental sensors Opening sensors Weather data	Outdoor temperature	Seasonal differences Gender Floor level Personal preferences	Daylight saving practices Facade orientation Schedule	Position	It focuses on end-of-day window position

Table 12. List and main details of the articles analyzed in the literature review *(continues on next pages)*

M. Yao, B. Zhao (2017)	3 months (Spring)	9 apartments	Beijing, China	Environmental sensors Opening sensors	Outdoor temperature	Outdoor humidity	Indoor air quality	Open/close action	$PM_{2.5}$ causes windows to close if it exceeds a certain threshold
Y. Zhang, P. Barret (2012)	16 months	333 office rooms	Sheffield, UK	Environmental sensors Photo of facade Survey	Outdoor temperature	Sunshine hours Solar radiation Indoor temperature Outdoor humidity Wind speed	Rainfall	Open/close action	Orientation and temperature difference between rooms are important factors
S. D'Oca, T. Hong (2014)	24 months	16 office rooms	Frankfurt, Germany	Data cluster analysis	Indoor temperature Arrival/leaving time Time of the day Outdoor temperature	Personal preferences Habits Attitudes	-	Open/close action Position	Data mining approaches to behavioural studies identify hidden motivational patterns
S. Pan et al. (2019)	6 months (transition seasons)	5 office rooms	Beijing, China	Environmental sensors Opening sensors Presence Gauss distribution	Outdoor temperature	Indoor temperature	-	Position	-
X. Zhou et al. (2018)	3 months (Summer)	1 open plan room	Nanjing, China	Environmental sensors Survey Monitoring schedule	Outdoor temperature Schedule Air conditioner	-	Outdoor air quality	Open/close action	It identifies 3 clear patterns between ventilation and outdoor temperatures
Z. Shi et al. (2018)	18 months (in total)	2 hospital wards	Nanjing, China	Environmental sensors Opening sensors $PM_{2.5}$ data	Indoor temperature Indoor humidity Opening size Seasonal differences	Outdoor temperature Rainfall Solar radiation Indoor air quality	Wind speed Wind direction Indoor air quality Time of the day Day of the week	Open/close action	Indoor temperature and relative humidity are found relevant in all seasons
Y. Wei et al. (2019)	3 months (transition seasons)	5 office rooms	Beijing, China	Environmental sensors $PM_{2.5}$ sensors Presence Markov chain	Indoor temperature Outdoor temperature Outdoor humidity Wind speed	Solar radiation Outdoor air quality	-	Position Open/close action	The authors consider wind speed and humidity influencing window opening

H. Mo et al. (2019)	4 months (transition season)	6 apartments	China (hot summer, warm winter region)	Environmental sensors Opening sensors $PM_{2.5}$ sensors XG Boost algorithm	Indoor temperature Outdoor temperature Indoor humidity Indoor air quality	-	-	Position	-
F. Naspi et al. (2018)	8 months (no Winter)	3 office rooms	Ancona, Italy	Environmental sensors Opening sensors	Schedule Outdoor temperature Indoor temperature	Indoor temperature	Indoor air quality	Open/close probability Open/close action Open portion	It indicates that actions on windows start at arrival based on typical temperature
V.M. Barthelmes et al. (2017)	3 months (spring)	1 apartment	Copenhagen, Denmark	Environmental sensors Opening sensors Bayesian Network	Time of the day Indoor air quality Indoor temperature Outdoor temperature	Wind speed Illuminance level	Day of the week	Open/close action	It suggests that behavior is more frequent during mornings and nights
Z.D. Belafi et al. (2018)	8 months (no Winter)	2 classrooms	Budapest, Hungary	Environmental sensors Opening sensors Interviews	Rules inside the group Habits Indoor temperature Outdoor temperature Schedule	-	-	Open/close action	It finds that windows are more used in the moring just in one classroom
B. Jeong et al. (2016)	7 months (in total)	20 apartments	Seoul, South Korea	Environmental sensor Opening sensors PM_{10} sensors Survey	Indoor temperature Indoor air quality	Schedule Time of the day Period of the year	-	Open/close action	The authors suggest that temperature drop is good to explain closing behavior
J. Hou et al. (2017)	4 months (winter)	20 dining rooms and bedrooms	Tianjin, China	Meteorological data Survey $PM_{2.5}$ data	Indoor air quality Outdoor air quality Wind speed Rainfall Seasoonal differences	-	-	Open/close action	Indoor and outdoor air quality is more related to opening behavior while bad weather and noise for closing

N. Li et al. (2015)	2 months (transition season)	1 office building	Chongqing, China	Environmental sensors Opening sensors Monte Carlo model	Outdoor temperature Indoor air quality	-	-	Open/close action	-
R.V. Jones et al. (2016)	12 months	7 apartments (bedrooms)	Torquay, UK	Environmental sensors Opening sensors	Indoor temperature Outdoor temperature Wind speed Time of the day Seasonal differencess	Outdoor humidity Indoor humidity Rainfall	Outdoor humidity Solar radiation	Open/close action	The authors say that seasonality change importance of main drivers
C. Sun et al. (2019)	6 months (Summer and Winter)	10 offices	Harbin, China	Environmental sensors Opening sensors Fan and AC controls Survey Data mining	Seasonal differences Habits Schedule Thermal comfort Outdoor temperature	Indoor humidity	Indoor air quality Outdoor noise Outdoor air quality Time of the day	Open/close action Opening duration	The authors indicate that many office workers left windows always open for the entire summer and all-closed during winter
Y. Zhai et al. (2019)	12 months	1 office building	Alameda, California	Environmental sensors Presence (camera) Survey	Outdoor temperature Seasonal differences Time of the day	Indoor temperature	-	Open/close action	It concludes that people aware of natural ventilation use windows more effectively
Y Jian et al. (2011)	1 month	5 apartments	Beijing, China	Environmental sensors Survey	Outdoor temperature Indoor temperature Room typology	Indoor air quality	-	Open/close action	It considers different patterns combining use of window and door in the same room
S.Shi, B.Zhao (2015)	14 months (periodically)	8 apartments	Beijing, China Nanjing, China	Opening sensor Meteorological data Survey	Outdoor temperature Outdoor humidity Outdoor air quality	Seasonal differences	Wind speed	Open/close action	-

3.4. Development of a window system to support learning

This section describes the implementation of the theories related to Learning-By-Doing through the use of building systems. It is proposed the development of a window system called Learning-By-Ventilating Window (LBVW) capable of communicating the environmental parameters related to ventilation and comfort prediction during its use. Seven main phases were followed to arrive at the complete development of the system:

1. *General description of the user experience;*
2. *Exterior design, system architecture, and general control logic;*
3. *Assembly of the sensor modules for environmental data collection;*
4. *Programming and simulation phase of the UI interface;*
5. *Refining the user-system interaction algorithm;*
6. *Preliminary tests and physical realization of the prototype;*
7. *Evaluation of the prototype effects on learning and comfort.*

First, it was clarified the basic functioning of the LBVW system by describing the ideal operation considering three comfort scenarios. In ‘point 2’, I continued towards the preliminary design with the description of the system architecture and UI. Subsequently, in ‘point 3’, I proved that the sensor modules collected all the data of interest in the loop. In ‘point 4’, the raw data were inserted into formulas, setpoints, and ranges, constituting a software dedicated to simulating the UI and the Arduino programming code. Then, in ‘point 5,’ after identifying ideal user profiles (personas), three interaction algorithms were detailed based on learning towards comfort goals. In the sixth phase, there was the concrete realization of the prototype, implementing part of the operations described by the software. In the final stage, ‘Case Study II’ was organized, considering the participation of volunteers within the university. On that occasion, it was assessed the impact of the prototype on the initial learning process, IAQ, and comfort. ‘Points 6 and 7’ are described in the following chapters.

3.4.1. The concept of Learning By Ventilating Window (LBVW)

The basic idea of the LBVW is to make users aware of the effectiveness of natural ventilation for health and comfort. In practice, the window helps the user to understand how to ventilate the room naturally and quickly without excessive heat exchange between inside and outside. By observing the data projected into the glass when the window is closed, the user is aware of local conditions such as the concentration of CO_2, the difference in temperature between inside and outside, and whether outside comfort conditions are favorable to the opening. Thus, people are always connected with the local exterior even when there is a decoupling given by the use of highly insulating windows, by mechanical systems, or by the simple permanence in the internal environment for an extended period. In other words, it helps the user decide to open/close when he/she wants more comfort. Finally, as previously described, the idea of ‘control perception’ through the use of the window system is favored. This aspect is expected to produce benefits on comfort. Concluding, the window scope in practice is described in three simple points:

- Helping the user to clean the air of the room;
- Helping the user to decide to open/close when he/she wants comfort;
- Making the user aware of external conditions to be more in control.

In the following text, the window design and the system architecture are illustrated in detail.

3.4.2. The design of the system

The body of the LBVW system consists of two devices: the main window and a small unit to be placed on the opposite wall to monitor internal environmental data. ‘Figure 45’ (on the next page) shows the main components of the two devices.

The central window measures the temperature of the external air and the internal glass (through thermocouples), the exterior humidity, the wind pressure, the barometric pressure, and the presence of the user in front of the window (programmed up to 60cm) and the opening angle of the glass. Furthermore, it is possible to equip it with an axial extractor to increase the possibilities of adaptation. Finally, the separate wall system detects other primary data: the wall temperature (through an isolated thermocouple in contact with the wall), the air temperature and humidity, the indoor CO_2 at the height of the occupants.

User interaction takes place through information displayed in the glass. This feature could be introduced using Transparent Organic Light Emitting Device (TOLED), probably available at a lower price in the next future, as already illustrated by various models of televisions (see ‘figure 46’). For the prototype, in place of the expensive TOLEDs, the information was displayed by a computer screen near the central window system. Future versions of the LBVW prototype will adopt projectors, and a transparent adhesive panel applied to the outside of the glass.

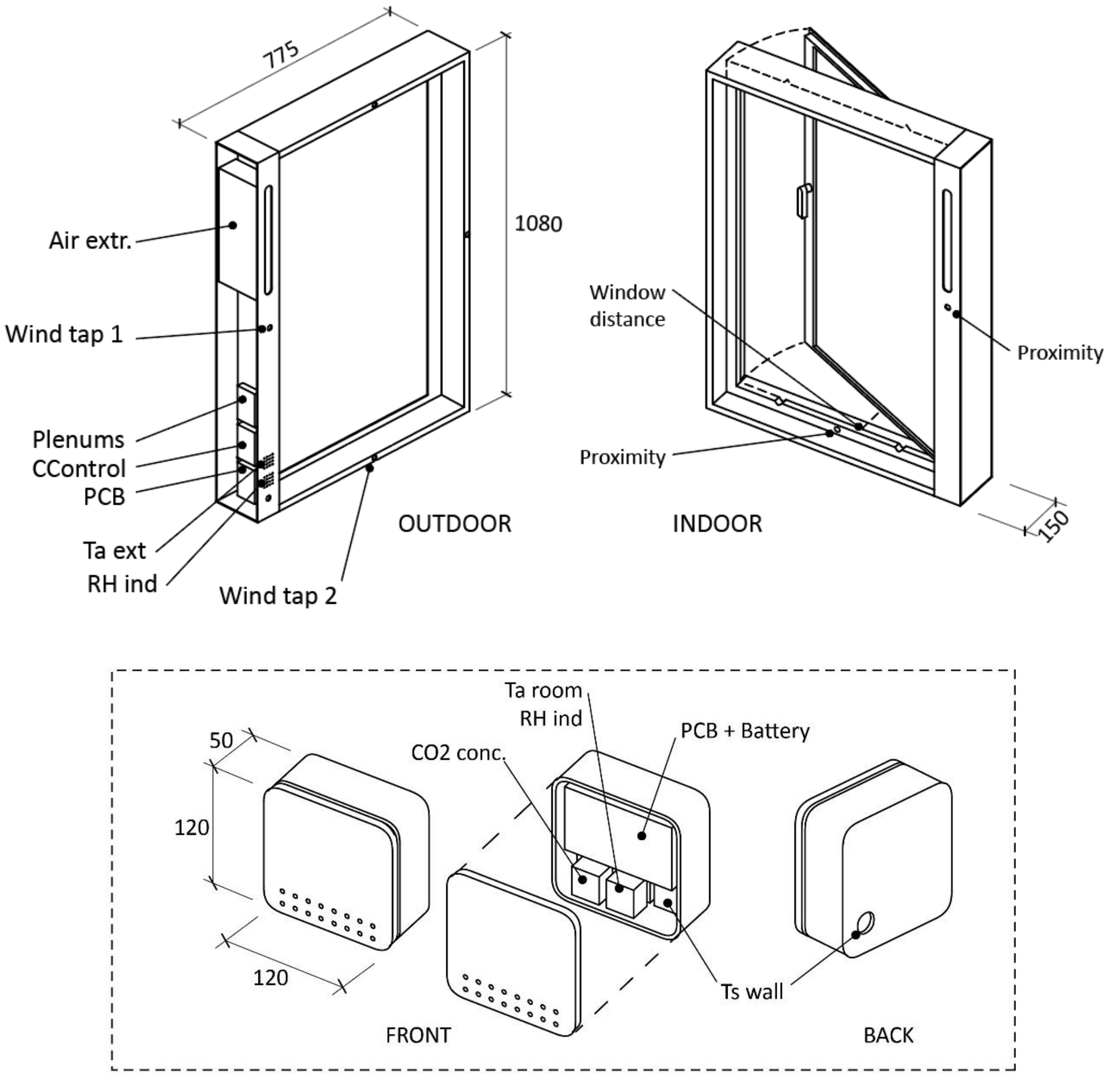


Figure 45. Illustration of the devices and components forming the LBVW system (above the main window and below the wall unit).

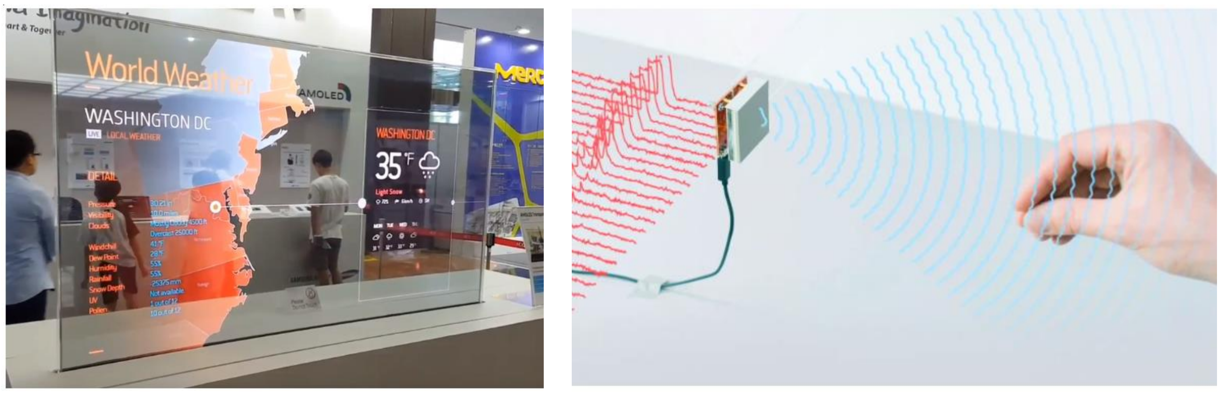


Figure 46. Possible technologies to be applied to the LBVW. A TOLED screen for the window glass (left). *Screenshot retrieved from www.youtube.com/watch?v=Lv46YU-X9Xs. A* high definition radar to recognize user gestures (right). *From https://atap.google.com/soli/.*

As added functionalities, the system could recognize the user's gestures, permitting contactless operation of the window-door or activation and graduation of the extractor. In this case, it could be obtained through the use of high-definition radar sensors type like SOLI chip, already used in some models of smartphones. In the case of the prototype, I concentrated on the data collection part, simulating the UI in the Simulation Software.

In the next subsection, the system architecture is described with particular attention to the formulas that permit the conversion of raw data into the information provided to the user.

3.4.3. The system architecture and control logic

The architecture of the LBVW system is based on a modular system. In this regard, embedded technologies dedicated to the control of small environments are commonly divided into four modules:

1. The sensors modules inserted in the environment;
2. One or more Monitoring Stations (MS), which is connected to the sensor modules, consists of a robust module that sends uninterrupted signals to the Control Center;
3. A Control Center (CC), or the module that connects the Monitoring Stations with the UI (it could be a computer or another PCB);
4. Cloud services, to connect the system to Internet Server services (for the prototype, Bluetooth protocol was adopted).

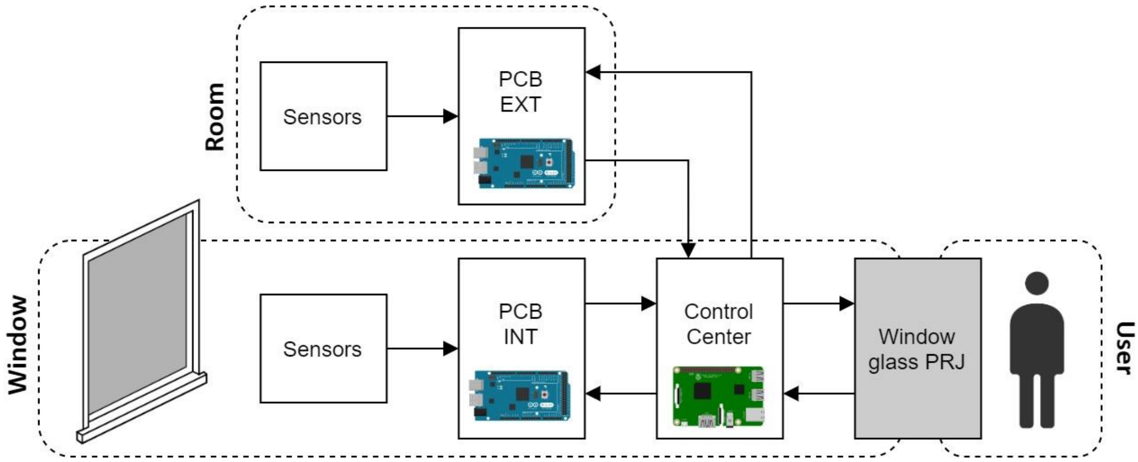


Figure 47. The system architecture of the LBVW prototype.

The two devices that make up the LBVW system have different configurations (see ‘figure 47’). The central window has a Monitoring Station (MS) consisting of a Printed Circuit Board (PCB), which receives the data from the sensors and a Control Center (CC), manages the data collected by the PCB, and transmits them to the window glass. Inside the room, the wall device consists of another PCB that sends the data to the CC via Bluetooth protocol.

The dedicated literature recommended using *Arduino* for the MS. It is a type of PCB based on the C/C ++ language, which owes its wide diffusion in the field of prototyping and robotics to the accessibility of its IDE software. Subsequently, the literature indicated the *Raspberry Pi* for the reception of data from the connected MS, the management of interfaces, and the more complex control algorithm (based on Python language).

Ideally, an *Arduino Mega2560* (ARDM) for MS and a *Raspberry Pi 3* (RPi) (connected via USB) for CC should have been used for the LBVW prototype. The RPi has a higher RAM capacity and is typically used for managing large displays. However, in order to simplify the process, the *Arduino* inserted in the central window prototype worked simultaneously as an MS and a CC. The main reason was that the thesis proposed an initial programming approach, leaving detailed coding to future developments (see also ‘section 3.5.1’). Additionally, the lack of a projector (or other large displays) to simulate the UI did not justify the use of the RPi. Eventually, an *Arduino Nano* (ARDN) was utilized for the external monitoring module simply for advantages on compactness and the need to manage less data than the central system.

The first step towards the assembly of the hardware and the code definition was describing the control logic of the system, which is shown as a behavior tree in ‘figure 48’ (on the next page). In specific, the diagram illustrates the logical steps between the actions of the system and user behavior.

(this part of the text is concealed due to possible conflicts with a patent application)

(this figure is concealed due to possible conflicts with a patent application)

Figure 48. Control logic showing the main functioning of the window.

(this part of the text is concealed due to possible conflicts with a patent application)

The control logic discussed was considered the base of the algorithm of the program. In 'section 3.6', the user experience is modulated based on the proposed comfort scenarios to refine the overall process and to show how people can learn from the system.

3.4.4. Description of the collected data

One of the essential requirements of the system was to inform the user about the local environment. Therefore, the LVBW system had to monitor in the loop a series of necessary primary data (environmental and non-environmental), combine them into secondary equations and finally convert them into practical information in favor of adaptation. In the following table, the primary environmental data recorded by the LBVW system are listed.

Table 13. Primary environmental data recorded in the loop by the system.

	Parameter	Abbreviation	Unit
1.	Differential pressure of the wind	P_{diff}	[Pa]
2.	Air temperature indoor	T_{ind}	[°C]
3.	Air temperature outdoor	T_{out}	[°C]
4.	The surface temperature of the glass	$T_{s, glass}$	[°C]
5.	The surface temperature of the opposite wall	$T_{s, wall}$	[°C]
6.	Relative Humidity indoor	RH_{ind}	[%]
7.	Relative Humidity outdoor	RH_{out}	[%]
8.	CO_2 concentration indoor (IAQ)	$CO_{2, ind}$	[ppm]
9.	Atmospheric pressure	P_{atm}	[hPa]

In particular, the surface temperature of the opposite wall ($T_{s, wall}$) was located in a position as close as possible to the user. Subsequently, for the literature, the CO_2 concentration is a direct indicator of the IAQ and ventilation performance since it is a good surrogate of bio effluents to evaluate possible airborne infection risks [108]. Therefore, to simplify the prototype, I considered CO_2 concentration as the only index of the presence of other VOCs and indoor poor air quality, without taking into consideration further sensors dedicated to specific chemical compounds. Then, regarding primary non-environmental data, the system detected the parameter listed in ‘table 14’.

Table 14. Primary non-environmental data recorded by the system.

	Parameter	Abbreviation	Unit
10.	The proximity of the user from the window	U_{dist}	[cm]
11.	Window door distance	W_{dist}	[cm]
12.	Height of the window opening	W_h	[cm]
13.	The volume of the room excluded furniture	V_{room}	[m3]

For the first two data (10, 11), dedicated sensors were used, while the height of the window and the volume of the room were entered in the programming phase as invariable data. Once the primary data was obtained, secondary ones were defined as indicated in ‘table 15’.

Table 15. Secondary data derived from loop measurements.

	Parameter	Abbreviation	Unit
a.	Window door angle	γ	[degrees]
b.	Opening area depending on door angle	A_{eff}	[m2]
c.	Air velocity from pressure difference	U_{vel}	[m/s]
d.	Airflow depending on window opening	Q_{eff}	[m3/s]
e.	Air change rate	ACR	[1/s]
f.	Mean radiant temperature	T_r	[°C]
g.	Indoor operative temperature	T_{op}	[°C]
h.	Comfort limits depending on T_{op}	$T_{op,l}$	[°C]
j.	User presence	U_{pr}	[Y/N]

Using the primary and secondary data showed above, it was eventually possible to inform the user of aspects more related to practical use, intuition, and adaptation. The measurements, in this case, varied from quantitative to qualitative information.

The conclusive table (‘table 16’ on the next page) shows the UI data observed and judged by the user when interacting with the LBVW system. The idea was to create the occasions when the user could learn both with the assessment of real-time information and before/after comparison of monitoring data. For this reason, the primary and secondary data were converted in intuitive descriptions, using words and symbols on behalf of scientific units (see 'section 3.5.3' for more details).

Table 16. Tertiary data appearing on the UI of the LBVW system.

	UI information	Unit 1	Unit 2
i.	Display on/off	-	-
ii.	Air quality in the room	[good-mid-bad]	ppm
iii.	Temperature difference outside	[°C]	-
iv.	Air velocity	[lively-breeze-calm]	[m/s]
v.	Minutes to clean the air	[minutes left]	[m3/h]
vi.	Wind outside	[lively-breeze-calm]	[m/s]
vii.	Comfort outside	[cold-good-hot]	-
viii.	Opening angle	[degree]	-

3.4.5. Feedback modalities

The feedback system described in this subsection was simplified during the programming and prototyping phase. It is based on the Learning-By-Doing process (see 'Chapter II'), where the window collected data from the sensors and transmitted them based on three main feedback groups.

In 'figure 49', the first group (WFB1) communicates to the user the aspects related to discomfort without considering his/her distance from the system and is based on a configurable time range during which the signaling system was active. As default mode, the window sends information during daylight hours and in the user presence.

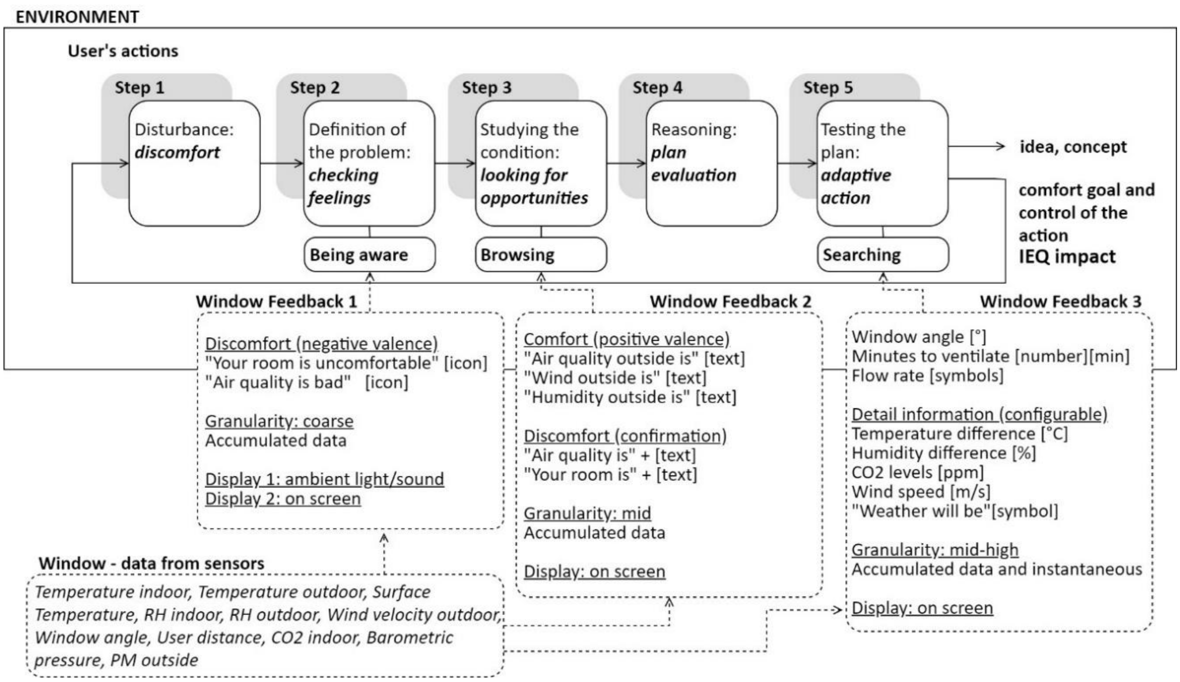


Figure 49. The framework of the Learning-By-Doing towards comfort with windows.

Specifically, the message content has a negative value and referred to the conditions "Your room is uncomfortable" and "Air quality is bad."

The display modalities of WFB1 is based on the user's 'awareness' attitude (passive reception of information). It is considered an ambient light accompanied by an audible alarm, and an icon showed on the screen. As a result, the granularity of the message is coarse (on or off) and based on the accumulation of data consisting of the data average (e.g., of the previous 5 minutes) and the ranges in 'table 20' (see 'section 3.5.3').

Timing must consider the user's behavioral granularity [61]. At that time, it is necessary to mediate the user's ability to notice the message and the time of intervention. Also, according to F Nicol, it makes no sense to evaluate comfort conditions in times of less than 30 minutes [20]. Therefore, an average of 5 minutes at intervals of 30 minutes each is considered a good compromise. Finally, if the user does not receive any signals but wants to monitor the situation, the interface enters the monitoring state based on more detailed feedback (WFB3, see below).

The second group of Feedback (WFB2) communicates comfort opportunities. Here the transmission of information begins when the user reaches the window. The message had a positive value and referred to the conditions "*outside air quality is good,*" "*wind is comfortable,*" and "*humidity is ok.*" Furthermore, the discomfort situation inside the room is shown in detail, to strengthen the WFB1.

In this step, the display modes originate from the user's 'browsing' level of understanding (attitude oriented to an undirected/active search for information). Then, the use of on-screen textual information accompanied by icons for faster browsing is considered. Consequently, the granularity of the message respects the stability of the text message because one of the issues is that the wind speed values are highly variable. According to this, the ventilation 'test 1' (see the next chapter) showed that the wind patterns changed approximately every 30 seconds. Therefore, an accumulation of data from 1-3 minutes is a trade-off between the stability of the information on the screen and the accuracy of the message, so as not to general false expectations.

The third group of Feedback (WFB3) indicates the details of the action and monitoring information. The content of the message is divided into three subgroups: information on the "*Window angle*"; action-related information such as "*Flow rate*" and "*Minutes to ventilate*"; and detailed useful data (configurable by the user) linked to "*Temperature difference,*" "*Humidity difference,*" " *CO_2 levels*", "*Weather will be ...*". Additionally, the information connected to the user's action is changed according to the discomfort message (air quality, humidity, or temperature issue) (see the next section for more details).

In this step, the display modes are linked to 'searching' and 'monitoring' levels (direct and active/passive attitudes towards information). Therefore, the messages are more detailed, and the metric is based on text, but also common or intuitive scientific terms (%, °, ° C, m / s, ppm). Thus, for the window door angle and wind speed, the granularity is high and instantaneous (< 1/sec). The objective is to give a sense of system responsiveness as interactive as possible at the time of the action. On the other hand, the information related to the operation has mid granularity (1-3 minutes) and the accumulation of the average data. In this case, the averages permit to maintain information stability and to help data interpretation.

The description given above defines the main pattern of interaction. According to that, the prototype saw some necessary simplifications.

Firstly, the values referred only to instant measurements (no averages) to lighten the coding. Secondly, the data referred to the outdoor Particulate Matter (PM), which define the message "outside air quality is good," were not considered when assembling the hardware and programming of the prototype. Finally, the monitoring operation, based on WFB3, showed graphs and periodic data (daily or weekly) selectable by the users. Thus, he/she could visualize the trend of temperature differences, wind speeds, and CO_2, and enrich the learning experience. However, the prototype did not provide this operation, concentrating on provisional data.

3.4.6. Description of the UI

As described in the previous subsection, when the user approaches the window, he/she is continuously informed about the external and internal parameters and received suggestions when opportunities arose in opening/closing. Specifically, the message is about how much time it takes to ventilate, and if the outside is comfortable to open.

The final version of the system includes the information display on the glass. 'Figure 50' shows the location of the interface inside the glass area, designed based on the current position of the handle, the type of door, and the position of the user based on the direction of opening.

The screen appears immediately when the user approaches (in case of discomfort signal) or with a gesture (in case of monitoring). The configuration is based on the three feedback moments (WFB1, WFB2, WFB3) and organized vertically based on the level of detail of the information. Therefore, the graphics is divided into three main sections:

1. Welcome section (based on WFB1 and low level of detail)
2. Central section (based on WFB2-3, and mid-level of detail)
3. Bottom section (based on WFB3, and high level of detail)

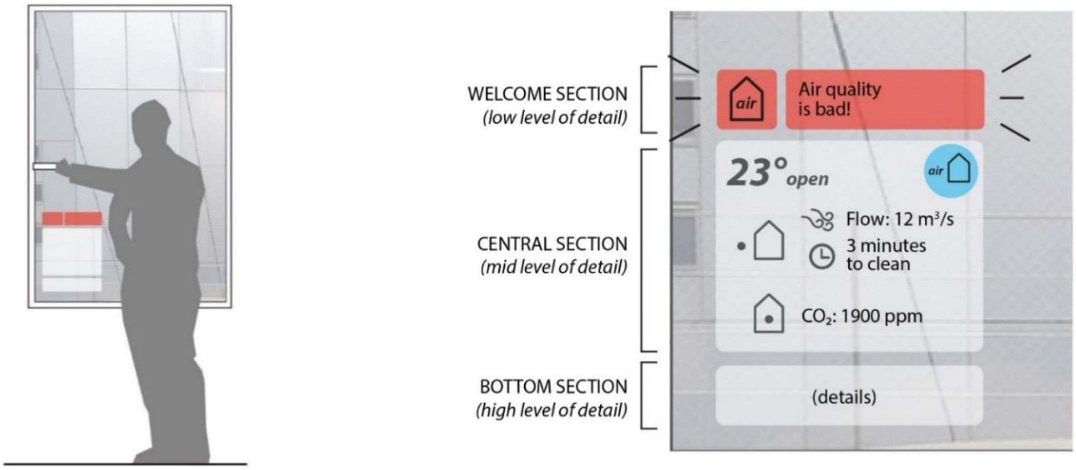


Figure 50. Position and general aspect of the User Interface.

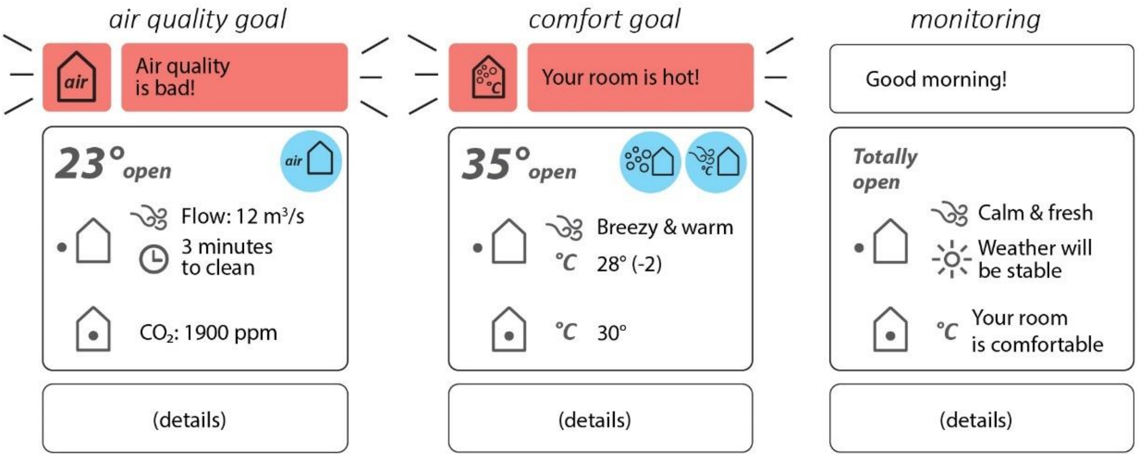


Figure 51. Variation of User Interface based on the discomfort message.

In the upper part (welcome section), there is the discomfort message, to confirm the ambient signal and specify the problem (for example, your room is hot/cold). Below, there is the central section, with the symbols of comfort opportunities (blue circle), and the information (always present) related to the window opening angle. The same area reports the information dedicated to the action and varies according to the type of discomfort alert. For example, in the case of poor air quality, the interface shows in real-time the flow rate, the time required to ventilate the environment, as well as the current CO_2 levels. Instead, in case the thermal discomfort message appears, the area highlights the wind speed and temperature difference between indoor/outdoor. Then, during routine control of the situation, the information preferred by the user is highlighted and alternated (see ‘figure 51’). Additionally, the lower part of the interface (bottom section) is dedicated to more detailed ‘searching’ information, with numbers and scientific values. The central and bottom sections are configurable by the user, depending on their preferences.

3.5. Programming of the system

After the initial description, design, and assembly of the prototype, the fourth phase of the development involved coding the algorithm of the monitoring station. To achieve that, I collected a series of formulas on comfort and ventilation to convert the data listed in the previous section. Additionally, the ranges to control the climate parameters were defined.

Once both were clear, I created the UI Simulation Software with *Excel*. The software helped to assess that the formulas worked as intended and to visualize the interface with changing values according to the data inputs. Then, it was useful to prepare the preliminary programming phase and to form the base for future code developments.

To support the programming inside the *Arduino* IDE, sensors manufacturers and the user community provide libraries and detailed explanations on code integration to build different programs. Generally, the code is organized into three main parts. The initial part is where libraries, functions, and 'pins' are included; a 'void setup()' code which is passed only one time and is used to locate and prepare the sensors; and a 'void loop ()' where data are continuously elaborated and sent to the serial monitor.

As already mentioned, the code regarding the *CC* module was considered outside the initial prototyping stage. However, the lack of detailed coding did not exclude the use of the control formulas, which were executed in the *Arduino* IDE software, to illustrate the basic principles of the prototype. The difference was the lack of flexibility of dedicated software and a more performing interface, which will be ideal for future versions of the LBVW prototype.

In the following text, I show the process of formulas selection and conversion within *Excel*. Subsequently, the control formulas and the monitoring codes inserted in the *Arduino* IDE are shown in the 'Annex C.'

3.5.1. Ventilation formulas of the program flow

This subsection illustrates the main formulas that compose UI Simulation Software and the *Arduino* IDE code. Specifically, the research concentrated on equations able to solve ventilation, comfort, and cinematic issues coming from the prototyping.

As already indicated in 'Chapter I,' the LBVW system involved the use of a door with vertical hinges, projecting outwards. This choice made the effective opening area more complex to calculate. Nevertheless, for this purpose, Van Paassen et al. (2015) addressed the problem through the use of an equation that approximates the complex geometry given by the side-hung windows [115] (see equation (1)).

$$A_{eff} = \sqrt{\frac{1}{\frac{1}{(w \cdot h)^2} + \frac{1}{\left(2 \cdot w \cdot h \cdot \sin\left(\frac{\alpha}{2}\right) + w^2 \cdot \sin(\alpha)\right)^2}}} \quad (1)$$

By adopting the same formula in the control software and keeping the main values of width (w) and height (h) fixed, it was possible to measure the effective area (A_{eff}) starting from the tangent of the angle (α) created by the window door.

By measuring the distance of the door from the frame, which forms the cathetus opposite the angle α, it was possible to obtain the value of the angle. With trigonometry, it was obtained the tangent and therefore its value, through the equations (2, 3):

$$tan\alpha = \frac{d_y}{d_x} \quad (2)$$

$$\alpha = \arctan(tan\alpha) \quad (3)$$

where d_y represents the door distance, and d_x is the horizontal distance of the measuring point starting from α. The arctangent of tan α was calculated to get the values in degrees (see equation (3)). Subsequently, it is described in detail the formulas relating to ventilation and indicated those inserted in the software.

Regarding airspeed, the values of the pressure difference between the interior and exterior of the environment were used. Specifically, the dynamic pressure (P_{dyn}) was calculated with the following equation:

$$P_{dyn} = \frac{1}{2} \cdot \rho \cdot U^2 \quad (4)$$

where ρ is the density of the fluid and v the velocity of the fluid squared. In the case of air density, the standard value is 1.225 [kg/m^3]. Consequently, it was possible to obtain the velocity from the following equation:

$$U_{vel} = \sqrt{\frac{2P_{dyn}}{\rho_e}} \tag{5}$$

According to the literature, the forces that determine the flow of ventilation through the openings are based on the pressure variations between inside and outside. In particular, they depend on temperature differences (chimney effect) and the force of the wind acting on the building. The total pressure difference is given by the following sum [116]:

$$\Delta P = \Delta P_{wind} + \Delta P_{buoyancy} \tag{6}$$

T S Larsen (2006) indicated that the wind component depends on the product of the pressure coefficient C_p, which varies according to the incidence on the facade (between -0.3 and -0.6), and the dynamic pressure. Consequently, if it is also considered the difference with the internal pressure P_i, the formula is as follows [116]:

$$\Delta P_{wind} = C_p \cdot \frac{1}{2} \cdot \rho_e \cdot U_{ref}^2 - P_i \tag{7}$$

where U_{ref} is the speed taken as a reference on the roof. Nevertheless, other authors can use different positions. For completeness, Larsen also indicated how to determine the pressure derived from the temperature difference. In the equation (8), the pressure difference measured at the window level increases with the distance between the entrance height H_1, the neutral floor H_0 (which can also occur within the same compartment) and the temperature difference:

$$\Delta P_{buoyancy} = \rho_e \cdot g \cdot (H_0 - H_1) \cdot \frac{T_i - T_e}{T_i} \tag{8}$$

where g is the gravity acceleration [m/s^2]. If (7) is rewritten based on the described formulas, the following equation is obtained [116]:

$$\Delta P = \left(C_p \cdot \frac{1}{2} \cdot \rho_e \cdot U_{ref}^2 - P_i\right) + \left(\rho_e \cdot g \cdot (H_0 - H_1) \cdot \frac{T_i - T_e}{T_i}\right) \tag{9}$$

The effects of temperature on wind pressure were not considered in the prototype to permit a more agile script.

From the pressure, it is possible to calculate the flow rate Q, which varies if it is analyzed transverse or one-sided ventilation. P Heiselberg (2002) described the procedure to determine the flow capacity [116]. In this respect, Q is proportional to the smaller surface of the opening

A_c in [m^2] and the air velocity U_c in [m/s] passing through the opening. It is obtained through the following equation:

$$Q = A_c U_c \tag{10}$$

The opening A_c is calculated by multiplying the area by the contraction coefficient C_c. At the same time, the air velocity is corrected by a coefficient C_v, which includes the frictions generated inside the compartment. The product of the last two coefficients is the so-called dispersion coefficient C_d. The theoretical speed v_{theo}, obtainable without any resistance, is the result of the following equation:

$$v_{theo} = \sqrt{\frac{2 \cdot \Delta p}{\rho_e}} \tag{11}$$

where Δp is the pressure difference, and ρ_e is the density of the outside air [kg/m^3]. Putting the two equations together and replacing C_d gives the Bernoulli's formula [114, 115]:

$$Q = \pm C_d \cdot A \cdot \sqrt{\frac{2 \cdot |\Delta p|}{\rho_e}} \tag{12}$$

where the dispersion coefficient is typically considered between 0.60 and 0.75 [115]. This value depends on the porosity, geometry, position of the opening, and the angle of incidence of the wind (among others) [117]. Similarly, some studies define C_d based on other data known in the equation. [118, 119].

As shown in the previous section, it is indicated the way for calculating the A_{eff} of a vertical pivot window (equation (1)). By replacing A_{eff} in (12), the next equation is obtained:

$$Q_{eff} = \pm C_d \cdot A_{eff} \cdot \sqrt{\frac{2 \cdot |\Delta p|}{\rho_e}} \tag{13}$$

'Equation 13' is the expression that was used to measure the flow rate in the LBVW system. Ideally, it should have considered the variation of the dispersion coefficient depending on the A_{eff}. However, for the simulation and prototype, it was adopted the standard value of $Cd = 0{,}65$.

Finally, to calculate the data referred to air changes (ACR), the room volume subtracting the permanent furniture (V_n) was introduced into the following equation:

$$ACR = Q_v/V_n \tag{14}$$

According to it, the air change rate value is 1 per second. To convert into minutes of ventilation, and to become useful information for the user, the inverse of ACR was simply divided by 60, as in the following expression:

$$Min\ left = ACR^{-1}/60 \tag{15}$$

3.5.2. Comfort formulas of the program flow

The LBVW system relied on two different expressions to provide comfort messages. For the evaluation of the external comfort conditions, the thermal comfort equation (16) was used. In this case, T_{om} referred to the temperatures average of the last ten years monitored by the Tokyo weather station (from the JMA website). The system considered people's adaptive comfort, which varies according to the climatic conditions during the year.

$$T_{comf} = \ 0.53\ (T_{om}) + 13.8 \tag{16}$$

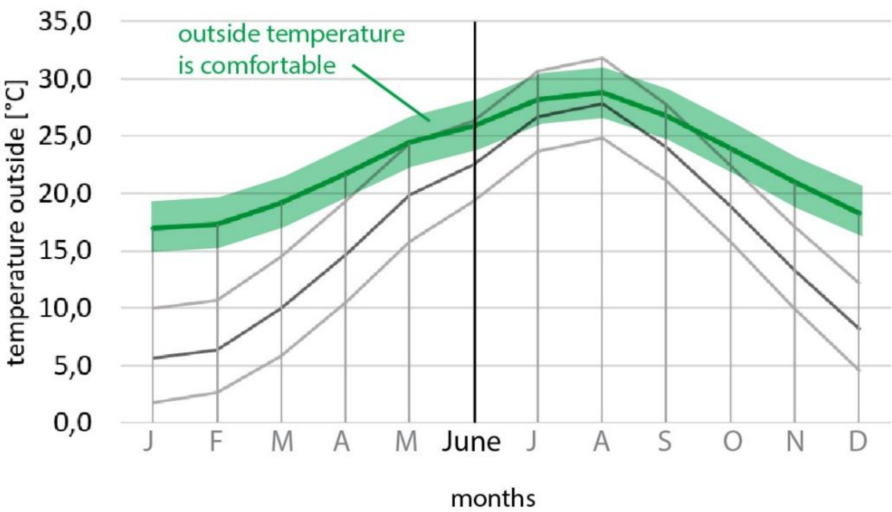


Figure 52. Temperature ranges of outdoor comfort during the year. *Adapted from Nicol (2016).*

Consequently, the window changed the reference to comfort temperatures once a month. Taking the example of June, the comfort range entered in the algorithm was 25.9 ± 3 ° C (see 'figure 52'). As the central days of the month were reached, and more the system became more precise (being that the users' body gets more used to the change of climate compared to the previous month).

Regarding internal comfort, the measurement was based on the operating temperature provided by ASHRAE 55, 2017. The average monthly temperature value was entered in equation (17) below, and the upper and lower comfort limits were given by the equations (19) and (20).

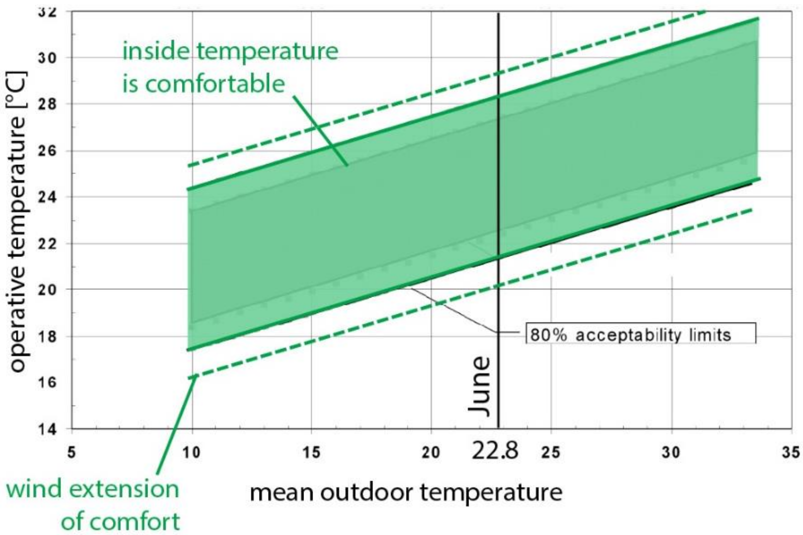


Figure 53. Comfort temperatures inside NV buildings. *Adapted from ASHRAE 55/2017.*

The comfort zone was enlarged with the contribution given by ventilation. Therefore, when the system detected that the window was open, the values of the T_{op} was corrected based on the wind speed, and the comfort zone was extended (see figure above).

ASHRAE/55 inserted ventilation influence inside the formula of operative temperature. For the equation, it is necessary to know the mean radiant temperature (T_r) and some coefficient related to wind velocity. In the case of T_r, a simplified method was adopted, which includes the average between T_{ind}, $T_{s,\text{wall}}$, and $T_{s,glass}$ as in the formula below.

$$T_r = \frac{T_{ind} + T_{s,wall} + T_{s,glass}}{3} \qquad (17)$$

Then, the value of T_r was inserted in the operating temperature formula (T_{op}), which is considered an indicative datum to describe comfort, together with T_{out} averages. Based on ASHRAE 55/2017 Appendix A [120], the equation is the following:

$$T_{op} = C_{av} + T_{ind} + (1 - C_{av})T_r \tag{18}$$

where C_{av} is a coefficient that varies according to airspeed (U_a). As a reference, ASHRAE indicated the following values reported in the 'table 17'.

Table 17. Coefficient C_{av} used to calculate the operative temperature. *Adapted from ASHRAE 55/2017.*

U_a < 0.2 m/s	**0.2 to 0.6 m/s**	**0.6 to 1.0 m/s**
C_{av}=0.5	C_{av}=0.6	C_{av}=0.7

Indoor and outdoor temperatures were considered to mix based on the ventilation level and to provide indications of comfort when opening the window. Finally, the operating temperature was used to predict the comfort effects of the combination of air temperature with wind speed.

Always ASHRAE indicated the limits of the T_{op} based on the 'prevailing mean outdoor temperature' (approximated to the 'mean outdoor temperature' as suggested by [20]). The formulas to obtain the limits were the following (adapted from [120]):

$$T_{op,sl} = 0.31 \cdot T_{om} + 21.3\ °C + U_c \tag{19}$$

$$T_{op,il} = 0.31 \cdot T_{om} + 14.3\ °C - U_c \tag{20}$$

where *sl* and *il* are the superior and inferior limit, respectively, and refer to comfort at 80% acceptability (see 'Figure 54', represented by the green lines). Particularly, from the moment that the user could manually adapt to the window, no upper airspeed limits were considered [120]. Besides, as indicated by G Bragger (2004), during behavioral studies in office buildings in the UK, the highest indoor wind speeds monitored during the analysis, received only 3% of negative votes [113].

Table 18. Increase of comfort limit based on air velocity. *Adapted from ASHRAE 55/2017.*

Average U_a = 0.6 m/s	**Average U_a = 0.9 m/s**	**Average U_a = 1.2 m/s**
U_c=1.2°C	U_c=1.8 °C	U_c=2.2 °C

As a result, people welcome different air velocities as long as the wind can be controlled. Finally, based on the airspeed, comfort zone limits could be extended according to the values indicated by ASHRAE (see 'table 18'). This coefficient (U_c) was inserted in equations (19) and (20) to complete the formula.

To conclude, in the table below, there are the equations integrated into the system code. The following subsection discusses the passage between numeric data and the information displayed in the UI.

Table 19. List of formulas utilized for the system. In bold, the data obtained from sensors.

Ventilation formulas	
1) Flow rate	$Q = \pm C_d \cdot Aeff \cdot \sqrt{\frac{2 \cdot \lvert \Delta \boldsymbol{p} \rvert}{\rho_e}}$
2) Area of the opening	$A_{eff} = \sqrt{\frac{1}{\frac{1}{(w \cdot h)^2} + \frac{1}{\left(2 \cdot w \cdot h \cdot sin\left(\frac{\alpha}{2}\right) + w^2 \cdot sin(\alpha)\right)^2}}}$
3) Opening angle	$\alpha = \arctan(tan\alpha)$ $tan\alpha = \frac{\boldsymbol{d_y}}{d_x}$
4) Air change rate	$ACR = Q/V_n$
5) Minutes to ventilate	$Min\ left = ACR^{-1}/60$
Comfort formulas	
6) Comfort Outside	$T_{comf} = 0.53\ (T_{om}) + 13.8$
7) Operative temperature	$T_{op} = C_{av} + \boldsymbol{T_{ind}} + (1 - C_{av})T_r$
8) Comfort limits (80%)	$T_{op,l1} = 0.31 \cdot T_{om} + 21.3\ °C + U_c$ $T_{op,\ l2} = 0.31 \cdot T_{om} + 14.3\ °C - U_c$
9) Mean radiant temperature	$T_r = \frac{\boldsymbol{T_{ind}} + \boldsymbol{T_{s,wall}} + \boldsymbol{T_{s,glass}}}{3}$

3.5.3. Key parameters and control ranges

To have the possibility to yield a qualitative textual message inside the UI, I listed a series of ranges and identified terms to describe them. 'Table 20' reports the limits that constitute the ranges of the system algorithm. Specifically, seven-value scales were considered for RH, wind temperature, operative temperature, and four-value ones for wind speed and CO_2 levels. In the case of RH, the acceptable range between 30 and 70 was considered, being 'slightly high' and 'slightly low' still acceptable. For external values, I followed increments of 10%.

The classification of the wind speed is generally based on outdoor measurements. Therefore, it was difficult to find a suitable denomination to describe the internal air movement. The National Oceanic and Atmospheric Administration (NOAA) website indicated the absence of wind at values lower than 0.4 m/s and 'light air' between 0.4 and 1.34 m/s (no movement of leaves). In the meantime, it is defined as 'light breeze' starting from 3.5 m/s, which causes the lifting of leaves from the ground [121]. But as known, people perceive wind speed on the skin starting from 0.1 m/s, and a velocity higher than 3.5 m/s could be defined as 'strong,' considering that it provokes movement of sheets inside the room.

Furthermore, regarding the aspects of comfort, ASHRAE 55 did not indicate any upper limit to ventilation provided that is less than 1.3 m/s, or the end-user is in charge of it. At the same time, it suggested a range between 0.2 and 0.8 m/s as a comfort zone without local control [120]. Finally, a study by M Fountain (1994), who analyzed the relationship between air movement, operating temperature, and percentage of satisfied, indicated an acceptable range between 50% and 90% for values between 0.1 and 1 m/s [122]. Based on the information above, I proposed a range between 0.2 and 0.8 m/s called 'gentle,' subsequently 'breezy' between 0.8 and 3.5 m/s, and 'strong' for values above 3,5 m/s.

The ranges referred to the temperatures are typically defined when they are inside the comfort zone. However, precise classifications for values external to it are not indicated. The intervals indicating neutral temperatures were based on the equations (19) and (20), which delimit the comfort zone for 90% acceptability. Subsequently, to define slightly hot/cold, I referred to the limits of 80% acceptability (± 0.8 °C). In the meantime, the outdoor (wind) temperature was based on the comfort temperature indicated in (18). Notably, I considered a range of ± 3, which was the same indicated by the ASHRAE indoor comfort zone. In both indoor/outdoor temperatures, to classify the other steps, increments of 1 °C were proposed.

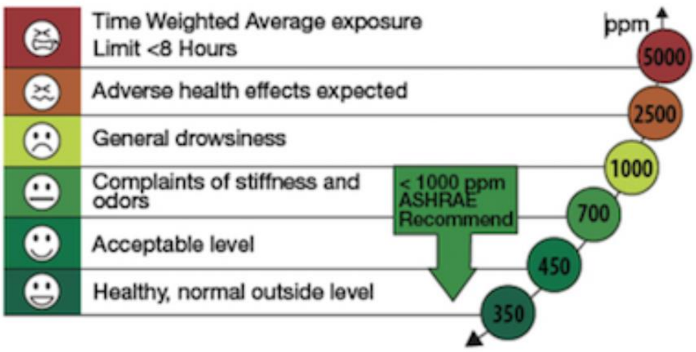


Figure 54. CO_2 ranges related to the effects on health. *From https://iotfactory.eu/the-importance-of-indoor-air-quality-iaq-for-business-performance-and-wellbeing/*

Regarding indoor CO_2 levels, the value of 1000 ppm is commonly recognized as the threshold beyond which a room is ineffectively ventilated. ASHRAE 62/2013, recommended levels below 1000 ppm [123] (see' figure 54'). A range between 1000 and 2000 is associated with bad air and drowsiness, while at higher levels (2000-5000), lack of attention and loss of productivity might be more frequent. Eventually, although I referred to 1000 ppm as the limit between good and bad air, other thresholds could be considered depending on the situation.

Table 20. List of ranges to convert analytical values in qualitative messages

Parameter	**Control Range**	**Message equivalence**
Relative Humidity	RH > 80	very high
	70 < RH < 80	high
	60 < RH < 70	slightly high
	40 < RH < 60	ok
	40 < RH < 30	slightly low
	30 < RH < 20	low
	RH < 20	very low
Wind speed	v < 0.2	calm
	0.2 < v < 0.8	gentle
	0.8 < v < 3.5	breezy
	v > 3.5	strong
Wind temperature	Tout > Tcomf + 5	very hot
	Tcomf + 4 < Tout < Tcomf + 5	hot
	Tcomf + 3 < Tout < Tcomf + 4	warm
	Tcomf - 3 < Tout < Tcomf + 3	pleasant
	Tcomf - 3 > Tout > Tcomf - 4	fresh
	Tcomf - 4 > Tout > Tcomf - 5	cold
	Tout < Tcomf - 5	very cold
CO_2 concentration	CO_2 < 700	very good
	700 < CO_2 < 1000	good
	1000 < CO_2 < 2500	bad
	CO_2 > 2500	very bad
Operative temperature	Top > Top,sl + 1.8	very hot
	Top,sl +0.8 < Top < Top,sl + 1.8	hot
	Top,sl < Top < Top,sl +0.8	slightly hot
	Top,il < Top < Top,sl	comfortable
	Top,il - 0.8 < Top < Top,il	slightly cold
	Top, il - 0.8 < Top < Top,il - 1.8	cold
	Top < Top,il - 1.8	very cold
Weather	1009.68 < P < 1022.14	stable
	P > 1022.68	warmer
	P < 1009.98	cooler

Finally, for the evaluation of the weather change, I utilized standard barometric pressure ranges. Nevertheless, the speed of growth and decrease of barometric pressure should have also been taken into account to provide more detailed forecasts on atmospheric variations (e.g., possibility of rain, snow) [124]. This option was finally discarded to simplify and lighten the coding structure.

3.6. Implementation of the UI Simulation Software

The UI Simulation Software was ideated to test the combination of formulas and to demonstrate the connections between the primary data collected by the sensors and the information received by the users. Additionally, it represented the necessary step towards the programming phase.

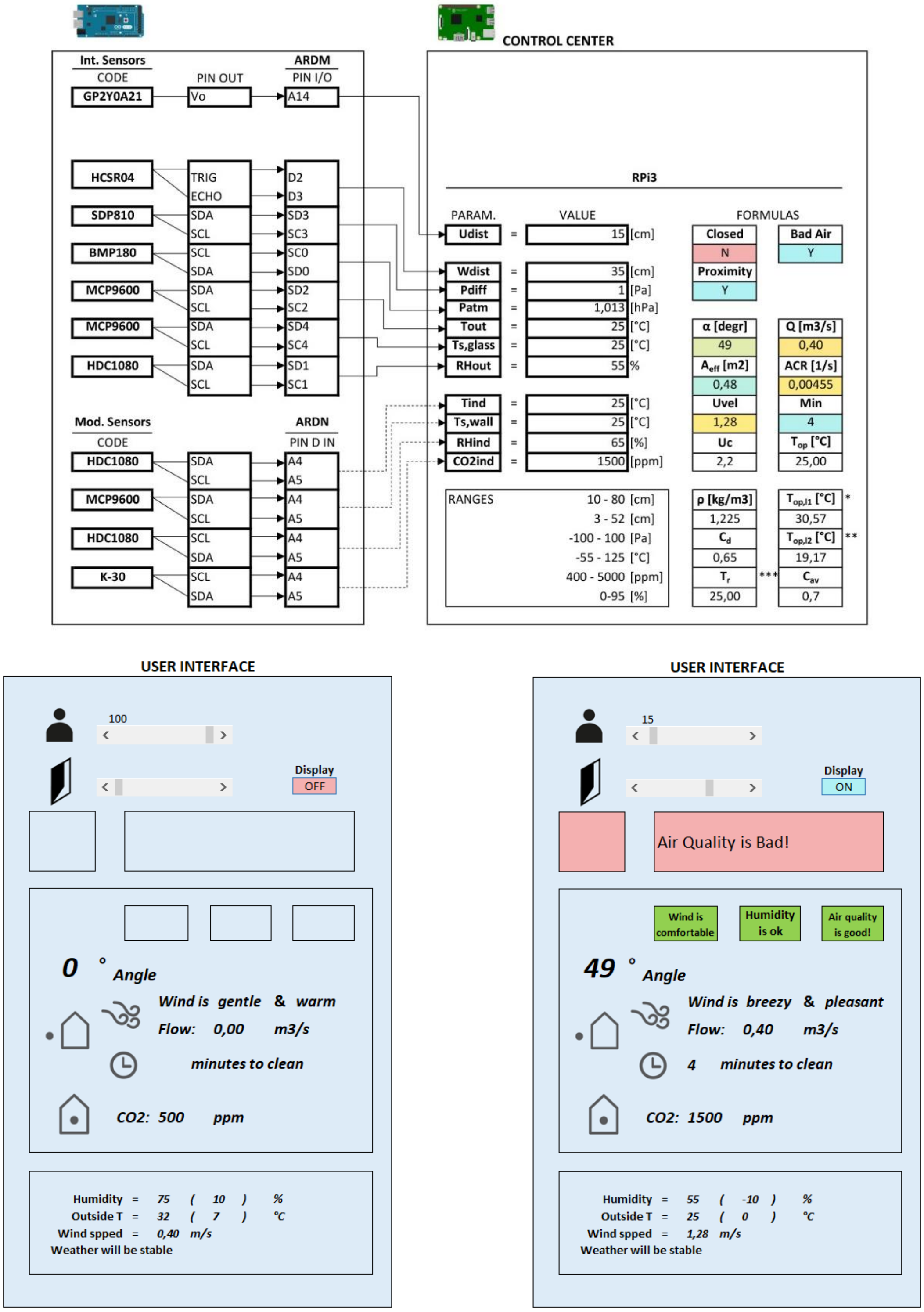


Figure 55. The UI Simulation Software: the control panel (above) and the user interface (below).

'Figure 56' shows the software control panel (see 'figure 55 (above)'). On the top left, there is a list of sensors divided by their location inside the main window, and the wall device. The black arrows show the connection within the sensor module and the PCB (ARDM). Then, the primary parameter channels (indicated in 'table 13, '14') pass to the CC area, where they are inserted into the equations (listed in 'table 19'). Here I indicated the working ranges (at the bottom) and the primary and secondary data (on the above left and right, respectively).

Changing the combination and entity of the primary values variated the secondary ones and the tertiary information displayed within the UI. For instance, 'Figure 55 (below)' shows a typical situation where the user controls natural ventilation to improve the IAQ. In this example, the user is not near the window, so the display is "OFF" (see bottom left). From the moment that the CO_2 rises, the user receives the notice "Air Quality is Bad! " which depends on the CO_2 concentration. Then, when he/she gets near the window, the display turns on. While the window is being opened, the "minutes to clean" the room air are displayed alongside the CO_2 concentration, which gradually decreases over time (see bottom right).

In conclusion, changing the environmental parameters, the position of the user, and the opening angle demonstrated how the system dynamically responded, variating the information displayed.

3.6.1. List of Formulas and IF statements

The following tables list the formulas entered in the user interface simulation software based on the conversion into *Excel* language. Being that this was a software to simulate the interface, it did not include the entirety of the ranges mentioned above. Additionally, weather change information was directly inserted in the *Arduino* code. Nevertheless, the complete intervals were considered in C++ when programming the *Arduino* for the prototype (see 'Annex C' as reference).

To permit the variation of the values within the UI, I used 'If Statements,' which are the basis of common programming languages. For example, the discomfort message "Air Quality is Bad!" appeared when CO_2 is above 1000 ppm. Therefore, it was translated in "IF (AND (*CO2ind* > = 1000; "Air Quality is bad!"; ""). The statements that involved more complex ranges adopted the same principle (for more details see 'tables 21, 22' on the next page). The following section describes how the interface served different comfort scenarios and triggered a long-term learning process.

Table 21. Statements inserted in the UI Simulation Software and based on the main formulas described in this chapter (in bold are indicated primary data from sensors).

Secondary data	**eq. #**	**Excel code**
α	(3)	= DEGREES (ATAN (***Wdist*** / 30))
A_{eff}	(1)	= SQRT (1 / ((1 / (0.62 * 0.98) ^ 2) +1 / ((2 * 0.62 * 0.98 * SIN (RADIANS (α / 2)) + (0,62 ^ 2) * SIN (RADIANS (α))) ^ 2)))
Q_{eff} (1)	(13)	(Cd * Aeff) * SQRT ((2 * ABS(***ΔP***) / ρ_e)
ACR (2)	(15)	=(Q/Vn)
U_{vel}	(5)	=SQRT(ABS(***ΔP*** *2/1,225))
T_r	(17)	=(Tind+Tswall+Tsglass)/3
C_{av} (from ASHRAE)	-	=IF(Uvel<=0,25;0,5;IF(Uvel<=0,65;0,6;IF(Uvel>0,65;0,7)))
T_{op}	(18)	=Cav*Tout+(1-Cav)*Tr
U_c (from ASHRAE)	-	=IF(Uvel<=0,6;1,2;IF(AND(0,6<Uvel;1,2>Uvel);1,8;2,2))
$T_{op,il}$	(19)	=0.31****Tout***+21.3+Uc
$T_{op,sl}$	(20)	=0.31****Tout***+14.3-Uc
U_{pr} (User proximity)	-	=IF(***Udist***<=60;"Y";"N")
(1) where Cd=0,65; ρ_e = 1,225 (2) where V_n = 88,5		

Table 22. Statements inserted in the UI Simulation Software regarding the main interface (in bold are indicated primary data from sensors) (continues on the next page).

UI information	**Excel code**
Discomfort message (IAQ)	IF (AND (***CO2ind***> = 1000; "Air Quality is bad!"; "")
Discomfort message (Indoor T)	= IF(*Top*>*Top,sl*+0.8,"Your room is hot!",IF(*Top* > *Top,sl*,"Your room is slightly hot",IF(*Top* < *Top,il*,"Your room is slightly cold",IF(*Top* < *Top,il* -0.8,"Your room is cold" ," "))))
Mins to clean the air	= (1/ACR)/60)

Display on/off	=IF(Upr="Y";"ON";"OFF")
Wind temperature	=IF(***Tout***<22,9; "cold"; IF(***Tout*** <21,9; "fresh"; IF(***Tout*** >28,9; "warm"; IF(***Tout*** >29,9; "hot"; "pleasant"))))
Wind speed	=IF(Uvel<0,2;"calm";IF(Uvel<0,8;"gentle";IF(Uvel<3,5;"breezy";" strong")))
Wind (comfort in summer conditions)	=IF(AND(OR(Uvel>0,2; ***Tout***<28,9); (***Udist***<60)); "Wind is comfortable";" ")
Humidity (comfort)	=IF((AND(***RHout***<=70; ***RHout***>=30; ***Udist***<60));"Humidity is ok";" ")

3.7. Refining the learning experience

This section discusses the fifth phase of the development, which was focused on demonstrating how users can learn from the LBVW system. As previously stated, the main principle was that the users improved their experience integrating different feedback based on the five steps of a Learning-By-Doing process. Additionally, they could learn by observing information details and daily/weekly monitoring reports. The system was considered capable of addressing the main sequence of actions indicated by the algorithms.

3.7.1. *Comfort scenario based on user's profiles*

The definition of user profiles helped to describe future target groups. According to N Dalton et al. (2016), architects should gain users' perspectives as HCI approaches. The main reason is that the use of fictional characters has the advantage of considering the typical user needs without designing for every single person [125].

I imagined three user profiles, which helped to define the possible targets of the LBVW system. For this scope, I adopted fictional users' names and illustrated distinct interests that the design might be able to address (see 'table 23' on the next page). Their interests were based on the conclusions of the literature review discussed at the beginning of this chapter. Then, from their description, comfort scenarios based on individual goals were determined.

'Table 24' (on the next page) clarifies the learning experience towards comfort described from the users' perspective. This description yielded distinct patterns of actions ('comfort goal 1, 2, 3') that were subsequently analyzed one by one alongside the information displayed by the system.

Table 23. Description of the user profiles indicated as possible targets of the system. (continues)

PROFILE A *(Air Quality User)*	**Robert** is concerned about **health**. He often uses the window to change the air, but he is worried about external pollutants that could enter the room. He likes to **have greater control of ventilation** and understand how **the window behaves**.
PROFILE B *(Thermal Comfort User)*	**Paul** usually **works at home**. He likes "sticking the head out" of the window and **enjoy the breeze**. Often, he is so concentrated in his work that he does **not recognize that outside wind is good** to increase his comfort.
PROFILE C *(Heat Balance User)*	**Sarah** is always concerned about **comfort and energy**. After getting up, she is not always sure how **outside conditions** are and **how she will feel opening**. Her goal is to **maintain the heat** inside but also to **solve air change** matters.

Table 24. Comfort scenarios referred to the profiles, described from the user perspective.

COMFORT GOAL 1 *(Air Quality)*	"When I'm using it, **I can see** if the air is good or bad. If it is bad, it **predicts me how long** it takes to ventilate. Then **I decide** whether to open the door and how much. If I choose to open, it **tells me in real-time** how long it will take to change the air **according to the opening**. While it's opened**, I can see in real-time CO_2 dropping,** but also wind speed, temperature, and humidity are changing. "
COMFORT GOAL 2 *(Temperature)*	"During the day, I can understand if **I will feel better** opening the window. When I approach it, I can see on the glass if it is **ideal outside** for keeping the window open. It **recommends me to open** when outside conditions are pleasant and **to close** when it starts to get cold. It is useful because sometimes I can decide to work far from the window."
COMFORT GOAL 3 *(Heat Balance)*	"During winter, **I like keeping the heat inside** my room. When the window says I should change the air, it also shows me if the **outside is too cold** to keep it open for a long time. In that case, I always decide to **ventilate as quickly as possible.** I think it is **also good to save energy** after switching off the heater".

The first scenario illustrates that the use of the window could solve air quality issues. At the same time, the second one is a midseason situation where the user wants to reach a comfortable temperature. The third one, instead, is imagined during winter (or summer) when the user aims to keep heat indoor and change air at the same time. The latter can be considered a mix of the first two goals.

3.7.2. Description of the interactions

In this subsection, the comfort scenarios previously listed are visualized and discussed. Each activity diagram proposed in 'figures 56, 57, 58' (on the following pages) indicates the main steps of the Learning-By-Doing process introduced in the previous chapter. Particularly, in the left column, there are the feedback and the actions of the system, while on the right, the sequence of users' choices towards their goal.

According to the first user profile, Robert's goal is to obtain a healthy environment. In the first step of 'figure 56', the system is monitoring in the loop, and the display is off. At that moment, Robert perceives the bad air quality or receives a message from the system (Feedback 1, indoor CO_2 is high).

Going into 'Step 2', Robert defines the problem and decides whether to follow the suggestion or follow his feelings. If the answers are positive, in 'Step 3', he reaches the window to confirm the indoor air conditions. At that moment, if the quality of the outdoor air is good, the window indicates an opening opportunity. At 'Step 4', Robert assesses whether to open the window, use the integrated extractor, or adapt in another way based on the information. At 'Step 5', he implements the plan by operating the window or the extractor. If the window is opened, Robert observes the WFB3 in the display (opening angle and flow rate). Eventually, he leaves the window open. At the end of the process, the system emits another signal if it senses that the air has returned to comfort levels. At this point, Robert sees the result, and if the conditions are satisfactory, he closes the window.

The second profile is Paul, who is interested in taking advantage of outside wind and temperature for comfort. In the first two steps of the diagram in 'figure 57', Paul can perceive a discomfort situation or receive a discomfort signal from the system. In particular, he approaches the window if the temperature signal is active or if it senses to have to open the window. At 'Step 3', he approaches the window and confirms the discomfort situation, analyzes whether the external wind is comfortable to open. If the answer is yes, in 'Step 4', Paul can decide to operate the window. During the action, the air velocity, the temperature, and the window opening angle are displayed. Then, Paul can decide whether to adjust the window according to the temperature or the wind speed. Eventually, he leaves the window open. At the end of the process, the window emits a sound and an ambient light, if it perceives a change in the quality of external comfort. At that time, Paul can decide whether it is better to close or keep open.

Finally, Sarah is aimed at maintaining her indoor temperature while changing air (see 'figure 58'). At 'Step 1', Sarah is already in a state of comfort but needs to ventilate when receiving the signal. Subsequently, at 'Step 2 and 3', she approaches the window and confirms the air quality issue, and also, if the outdoor air is good (in the case outside pollution is high, she can always use the integrated extractor). After air quality checking, Sarah can consider whether the wind is comfortable outside to open. At 'Step 4', based on the indications on the outdoor climate (e.g., if it is too cold), she may decide to ventilate for a short period. In the next step, during the action, she can see how many minutes it takes to properly ventilate the room according to the window opening angle and the state of the room door (among other factors). Eventually, Sarah leaves the window. At the end of the process, as soon as the internal CO_2 has returned to normal levels, the window sends a sound/light signal indicating the possibility to close. Sarah reaches the window and decides whether to continue ventilating or not.

Apart from the primary course of action, each user can take alternative paths. Particularly, in 'Step 3', without receiving any signal, they can also decide to control the situation by observing the data on the screen (based WFB3) or the daily/weekly monitoring reports.

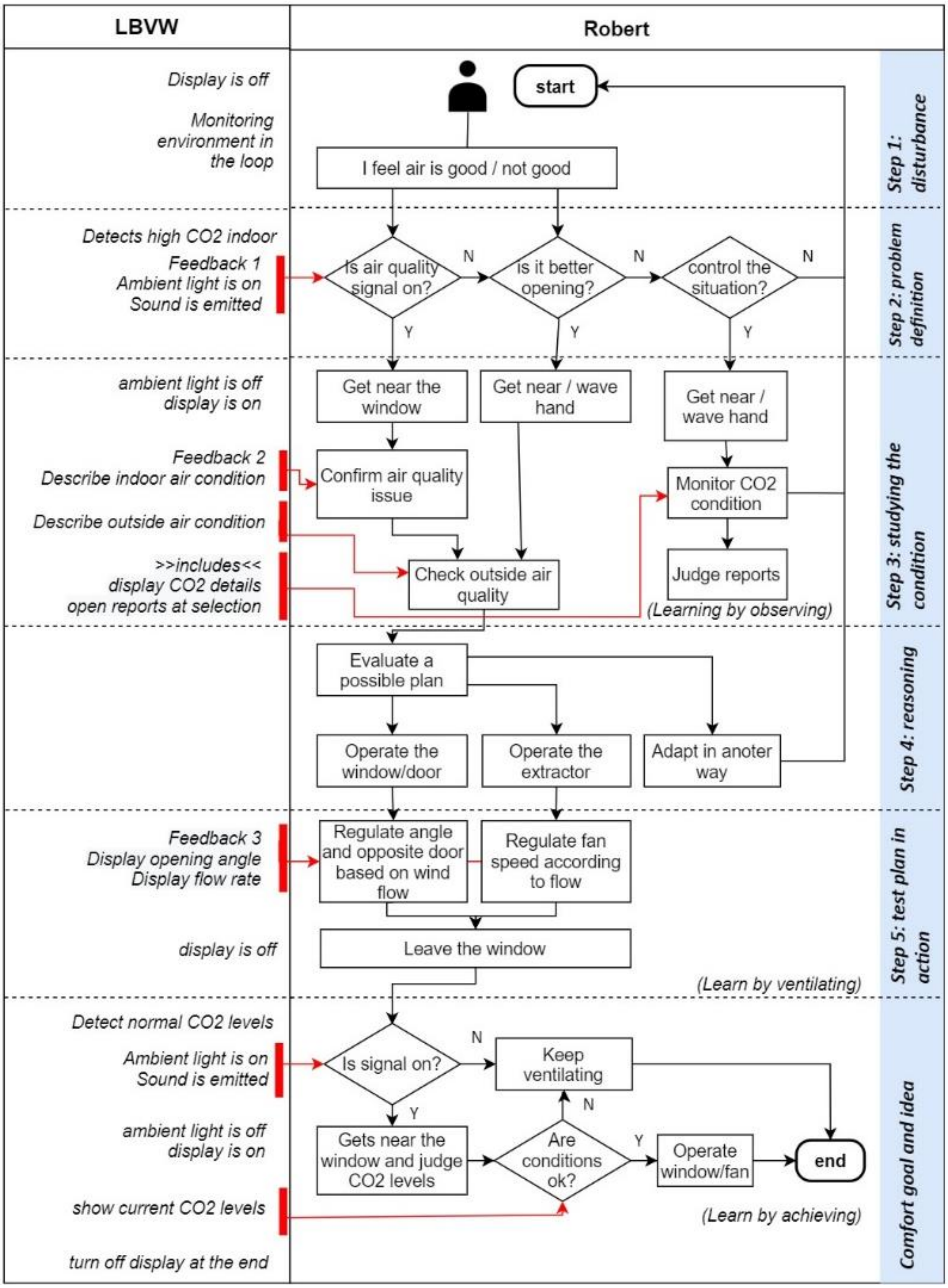


Figure 56. The interaction diagram according to Comfort Goal 1.

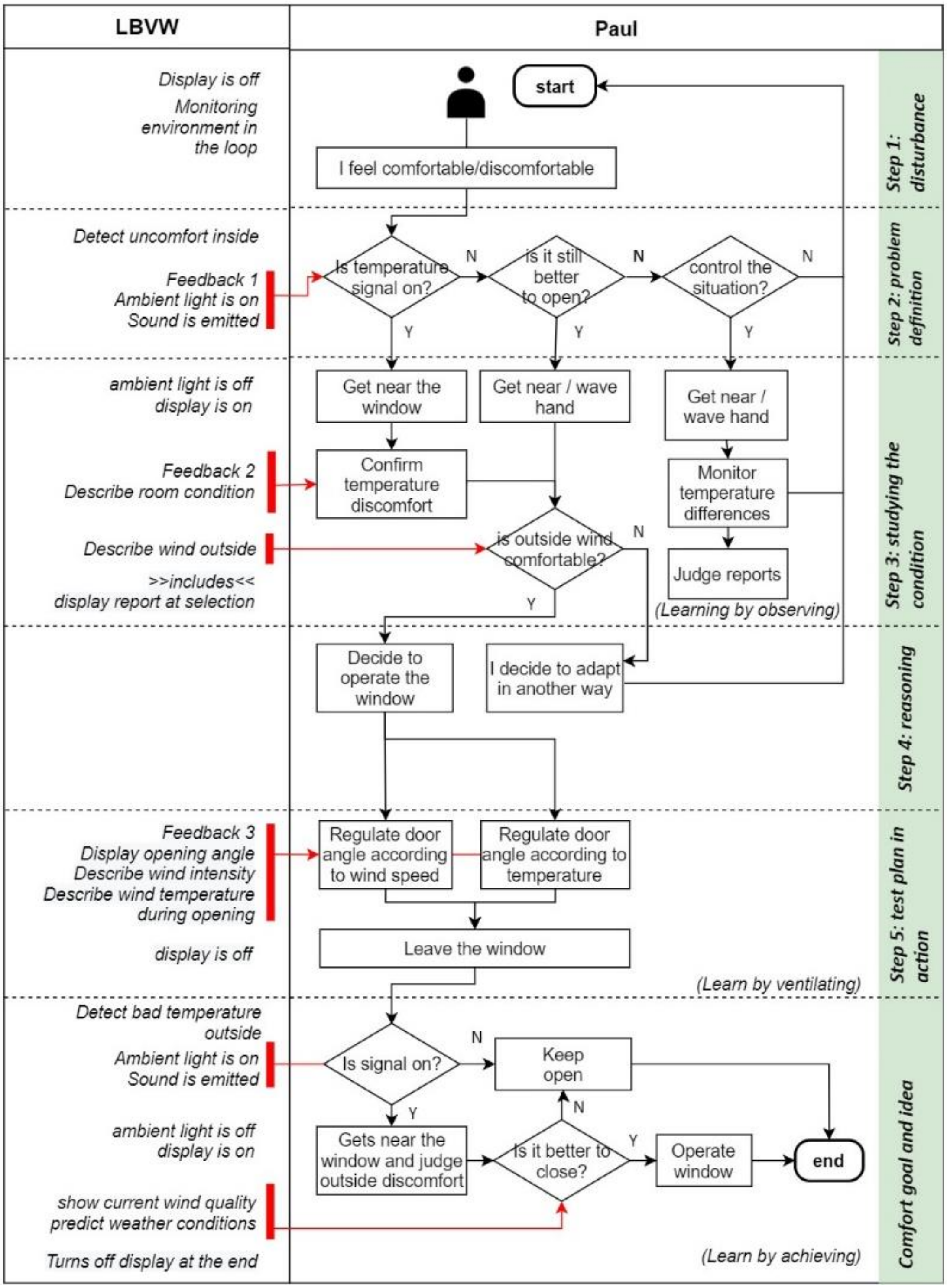


Figure 57. The interaction diagram according to Comfort Goal 2.

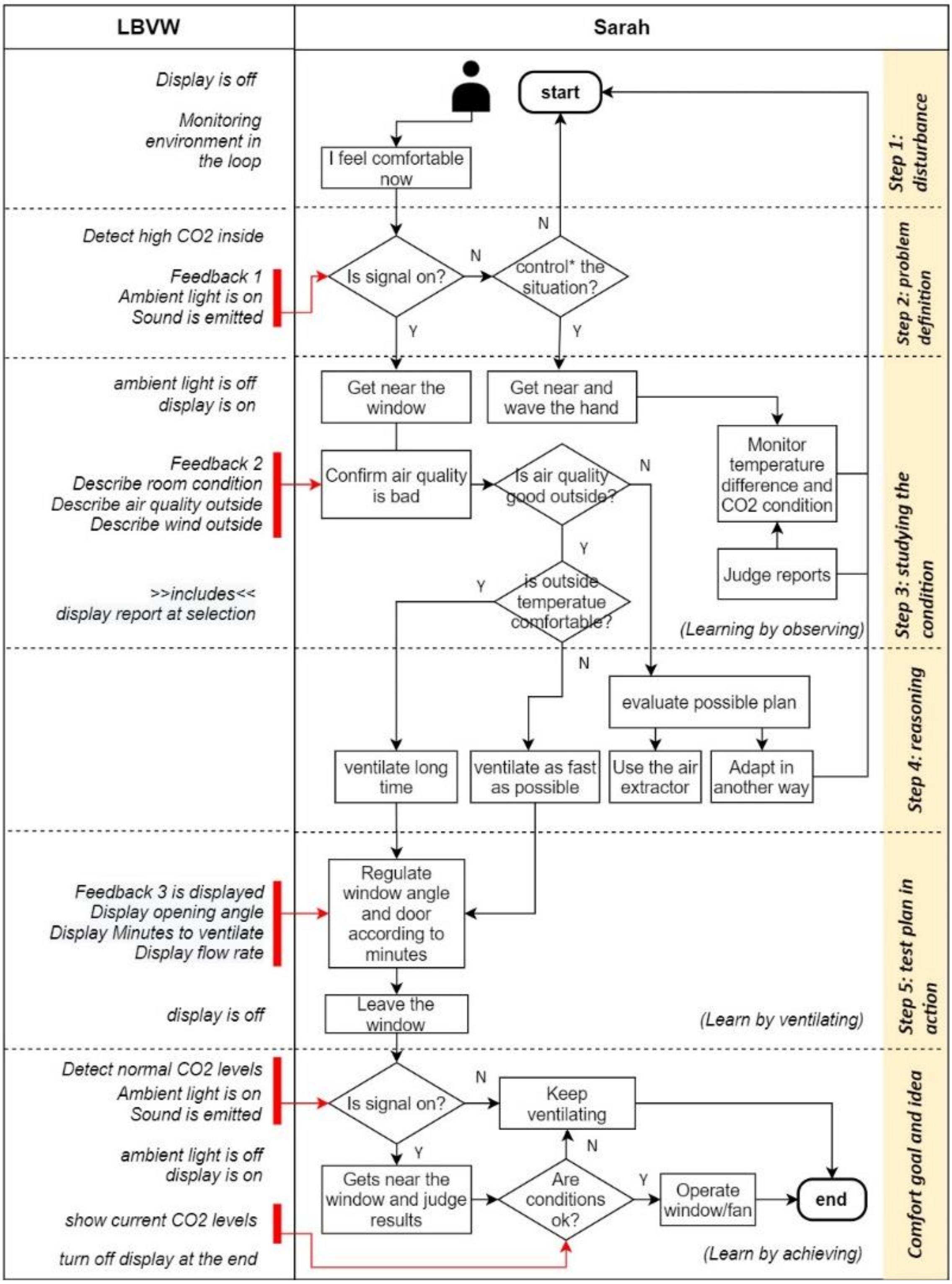


Figure 58. The interaction diagram according to Comfort Goal 3.

3.7.3. *Discussion and conclusions*

With the repetition of the activities previously described, the system was considered capable of producing gradual learning, impacting comfort, and indoor environment. With feedback suggestions, people might be able to adjust their needs to the very moment and place. Then, daily/weekly feedback reports referred to the user's interests might add insights into the process. Furthermore, there might be a possibility to save energy, especially when users are decoupled from the outside environment. Finally, the feedback, being integrated into the object (for example, unlike smartphone applications) could favor long-term use of the system.

Concluding, these scenarios could be realized following the indication provided by the system. The following chapter illustrates the LBVW prototype and demonstrates its capabilities to show the information described in the algorithms, regarding the mainstream of action (the functionality of daily/weekly reports is not implemented in the prototype). Eventually, it is discussed the conclusive case study with volunteers that tested the prototype in a semi-controlled environment.

3.7.4. *Perspectives on window learning*

A way to increase the efficacy of the LBVW system would be to implement machine learning for comfort achievements. The learning experience can also involve the window system itself, which might follow the user learning process in parallel. In this case, the system would also be dedicated to improving its performance and to make predictions on the user's behavior.

First, according to M Mehryar et al. (2018), alongside the data coming from the environmental sensors, the system could receive 'human-labeled training sets' [126]. In other words, the window could elaborate statistical predictions from a series of physiological data and anticipate the user's comfort state and consequent behavior. Furthermore, another advantage is that the system could adapt, through on-the-job improvements, to the different users and environments where it is located.

Second, regarding user feedback, the LBVW system could collect a sample of data from their body or analyzing comfort preferences. In the first place, computer vision applications could make the window recognize the user's skin temperature to identify his/her metabolism and thermal balance every time is in front of the window. For this scope, installing a thermal camera in the inner side of the window (combined with indoor/outdoor comfort data) would adjust comfort signals and information depending on the moment. Secondly, the window could receive feedback related to comfort sensations and feelings. For this purpose, through reinforcement learning, the system would evaluate users' votes on comfort/discomfort messages actively and maximize the system to match their perceptions. For instance, the paper by Y Zhao et al. (2013), already discussed in 'Chapter II,' is a clear demonstration of how a system (in this case, A HVAC system) learns from the users' complaints on acoustic and comfort performances of the appliance [78]. Transposing this approach to the LBVW, through reinforcement learning, it might be possible to adjust the indoor/outdoor comfort ranges (see the following comfort formulas) based on people's sensation votes and preferences during close/open window state.

Due to the extent of this work, the thesis concentrated on the human learning side, but I consider that machine learning applied to the system could improve the adoption of the system. For this reason, further study embracing these aspects will be carried out in future stages.

CHAPTER IV
DEVELOPMENT OF THE LBVW PROTOTYPE

4.1. Introduction

The basic function of the LBVW prototype was to record and display environmental data. The most important one was wind detection. In the first part of this chapter, it is discussed how to measure wind velocity data in the field, starting from the analysis of the methodologies shown in the literature. Subsequently, there is a description of the ventilation tests carried out to individuate the system configuration that provided better pressure measurements. The second part is dedicated to the prototype description and to demonstrate its sensing and data visualization capabilities. Finally, in the third part, it is reported a conclusive case study, which indicated the prototype as a support of the learning process described in 'section 3.7'.

4.2. Ventilation measurement methods

To create a prototype with a compact design capable of measuring the flow of air with enough accuracy, I studied the monitoring methods of other researchers and tested different alternatives.

The research applied to the study of natural ventilation through windows is mainly divided into 1) field studies, 2) laboratory studies with windows inside a controlled chamber, 3) and small-scale experiments (see 'table 25'). The articles found (see the table below) were generally dedicated to the measurement of ventilation efficiency, to the calculation of the dispersion coefficient, and in describing the dynamics of internal flows.

Table 25. List of authors reviewed, and type of measurement method applied.

Author	Year	Type of study	Method
Pan et al. [127]	2019	Field study	(a, b, c)
Gough et al. [128]	2018	Field study	(b, c)
Pabiou et al. [49]	2015	Field study; small scale	(b)
Richards and Hoxey [129]	2012	Field study	(b, c)
Pan et al. [130]	2019	Field study	(a, b)
Cruz et al. [118]	2016	Field study	(b, c)
Erhart et al. [114]	2015	Field study	(a, c)
Lo, et al. [50]	2012	Field study	(a, b, c)
Heiselberg et al. [119]	2001	Controlled chamber	(b, c)
Heiselberg et al. [116]	2002	Controlled chamber	(b, c)
Grabe et al. [131]	2014	Controlled chamber	(a)

(a) Tracer gas method; (b) Measurements with anemometers; (c) Measurement of pressure

The measurements methods adopted by the researchers were divided into three main methodologies, often used simultaneously to have a direct data comparison:

a. Tracer gas methods;
b. The use of thermal or ultrasonic anemometers;
c. Pressure differences measurements between two points of the building or from reference speeds.

First, concerning the tracer gas method, it is monitored the CO_2 decay present in the air, or it is injected for some time (using CO_2 or a mixture of other gases that require lower ppm) up to a reference value (e.g., 3500 ppm as in [114]). This technique is ideal for probing the effectiveness of windows in diluting or dispersing pollutants. In particular, Grabe et al. (2014) adopted a technique that involved the distribution of CO_2 sensors in a stratified way at different heights. They indicated that natural ventilation was most effective in levels close to the floor (e.g. [131]). Also, strategic positioning within one or several rooms and the use of desk fans to increase dilution (e.g. [127]) were implemented. In the case of the prototype functioning, for obvious design reasons, injecting tracer gas was not a viable solution. However, as already described, a CO_2 sensor installed wirelessly inside the room was utilized.

Second, indoor air velocity measurements are conducted with anemometers sufficiently sensitive to recognize very low air velocities. In the articles, the most utilized were the hot-wire and ultrasonic anemometers, both characterized by sophisticated technologies. The first probes measure the resistance of a metal wire (typically platinum) heated continuously and exposed to the airflow. The recorded temperature difference is converted into airspeed. Then, the second ones are even more accurate and measure the sound pressure between two transducers, which also helps to identify the direction of the flow. Thus, several authors used sensors in the center of inlet or outlet openings, or the center of the room. Specifically, although hot wire anemometers are accurate, they have problems related to the directionality of the flow at shallow pressures. The extent of the error is tested in previous paragraphs (see ‘subsection 2.3.4’). For the integration of anemometers inside the prototype, they were discarded due to their size, the impossibility of using them inside the room, and the difficulty of being connected to a single monitoring station, unlike other sensors based on digital protocols.

Third, the measurement of pressure differences depends on the calculation method adopted. Some researchers used cubic silos to determine the aerodynamic of wind and its pressure on the facade, considering its directionality [128, 129]. Arrays of taps (e.g., 7mm in diameter) were positioned at strategic distances on the facade and around the openings to determine pressure differences between interior and exterior or between facades under pressure and overpressure (see 'figure 59'). The taps pneumatically transmitted the pressure to a differential sensor through pipes.

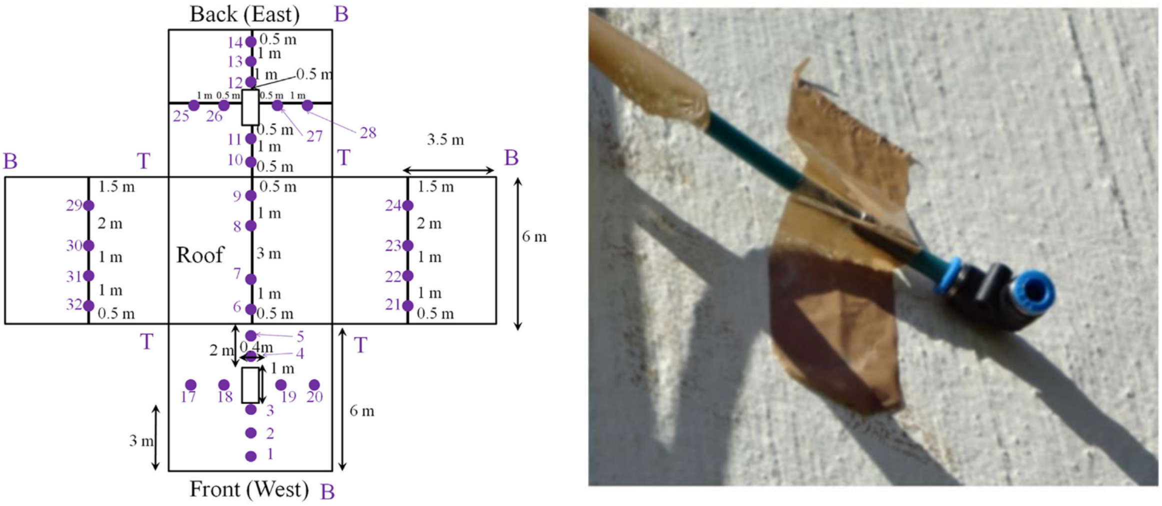


Figure 59. Scheme of pressure taps positioning on a full-scale testing cube (left). *From Gough et al. (2018).* An example of pressure tap (right). *From Cruz et al. (2016).*

For this purpose, H Cruz et al. (2019) showed the effectiveness of positioning the taps immediately outside the external frame of the window, in the centerline of the sides. Another point is that, since my goal was to calculate the average airflow of the entire opening, Cruz et al. suggested connecting multiple pressure taps to a plenum [118].

Subsequently, indoor reference pressures (dynamic or absolute) were placed immediately below the openings [128], or on the floor under the window [118]. Then, other articles indicated to connect one extremity of a differential sensor to taps on the roof, and the other two taps in the center of the tested window. In contrast, in the case of the measurement of dynamic pressure through the window, L Lo (2012) used the average values coming from an array of 32 pitot tubes distributed in three openings [50].

Concluding, for reasons of compact design, pressure measurements inside the prototype were taken locally around the opening, avoiding the use of pressure taps inside the room, on the roof, and obviously in the center of the window (for aesthetic and usability reasons).

In light of the above, for the first version of the prototype, two alternatives were analyzed: 1) the measurement of dynamic pressure via an array of seven pitot tubes connected to a plenum inside the frame of the window, one of them in a static position; 2) the use of four pressure taps collocated externally, connected via plenum, and one in the inner side of the window. Thus, I was able to test various monitoring possibilities before ‘Case Study II.’ As we will see, the second approach was more suitable for my purposes.

4.2.1. Uncertainties and constraints given by measurements

Apart from the uncertainties indicated by the literature, measuring ventilation with a window prototype added other critical points due to compactness and usability requirements. The next list represents the main aspects I considered as uncertainties:

- Constraints due to the realization of a design object (accepted uncertainty)
- Turbulent and variable pressure of winds (accepted uncertainty)
- Disadvantageous boundary conditions (solution: use of a DIY blower door)
- Use of averages instead of instantaneous pressures (accepted uncertainty)
- C_d value misused (solution: testing common values from the literature)
- Not considering window infiltrations (solution: weathering the curtain wall)
- Wind direction and angle (solution: use of two differential sensors)
- The position of the pressure sensors (solution: prototype with switchable taps positions)
- Use of standard air density (accepted uncertainty)
- Use pressure sensors instead of anemometers (accepted uncertainty)

4.2.2. Realization of a DIY blower door

To reduce the uncertainties related to the boundary conditions (primarily for the presence of a balcony and a patio outside), I decided to create a DIY blower door to generate a more constant and controlled pressure. Blower doors are insulating devices that are positioned in place of existing doors and consist of axial fans that cause pressurization/depressurization inside the tested environment. They are usually made to measure the level of airtightness of houses (whole-house pressurization tests), generating pressure differences in the range of 10 and 75 [Pa] between the inside and the outside [132]. They can be used not only to identify possible leaking spots and help in reducing consumption due to heating but also in studies on the discharge coefficient for more stable and repeatable measurements.

A blower door was considered particularly expensive, and precision equipment (adjustable fan and telescopic structure, pressure gauges, et cetera) not strictly necessary to conduct the prototype tests. Therefore, it was decided to build a wooden blower door of the compartment size, consisting of two extractors of different power (see ‘figure 60’).

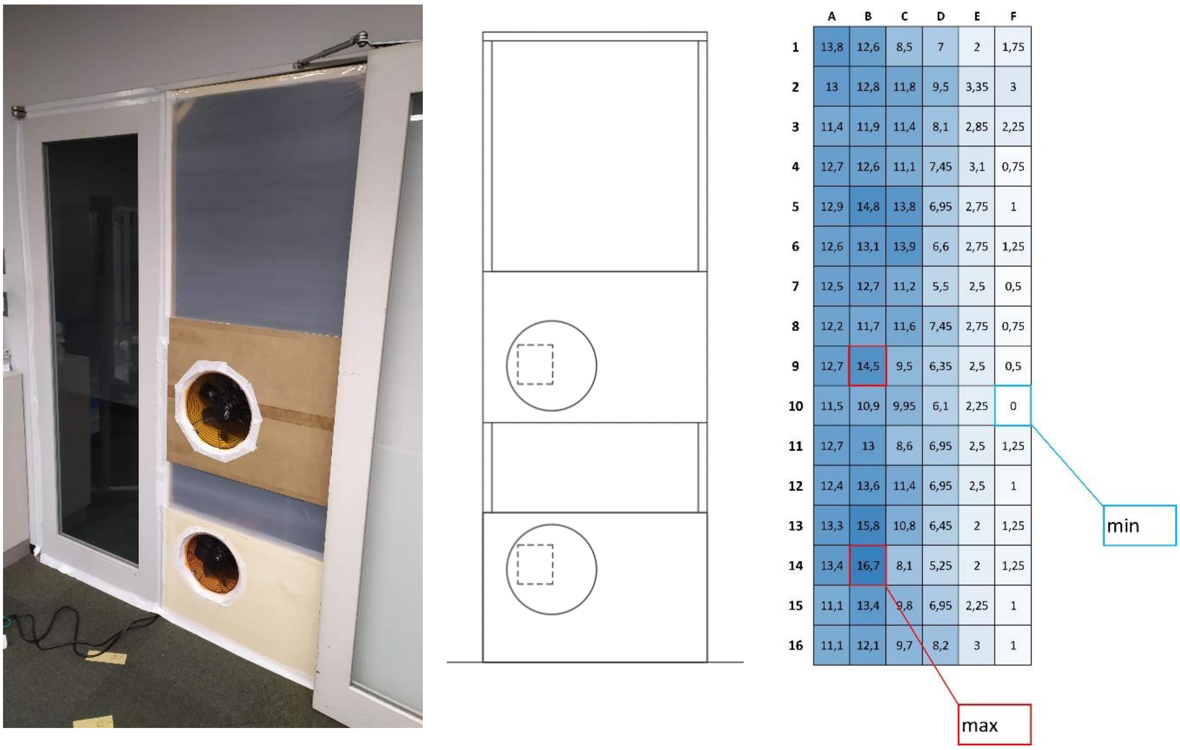


Figure 60. The DIY blower door installed in the testing room (left) and fan location referring to the maximum ventilation points encountered in following ventilation tests (center and right).

Table 26. Flow rate comparison of the DIY and a standard blower door.

	DIY Blower door		*Original Blower door*	
Air extractor	**m3/min**	**m3/h**	**m3/h**	
Low	50	3000	4900	**Min RPM**
Mid	71	4260	…	…
High (combined)	121	7260	7400	**Max RPM**

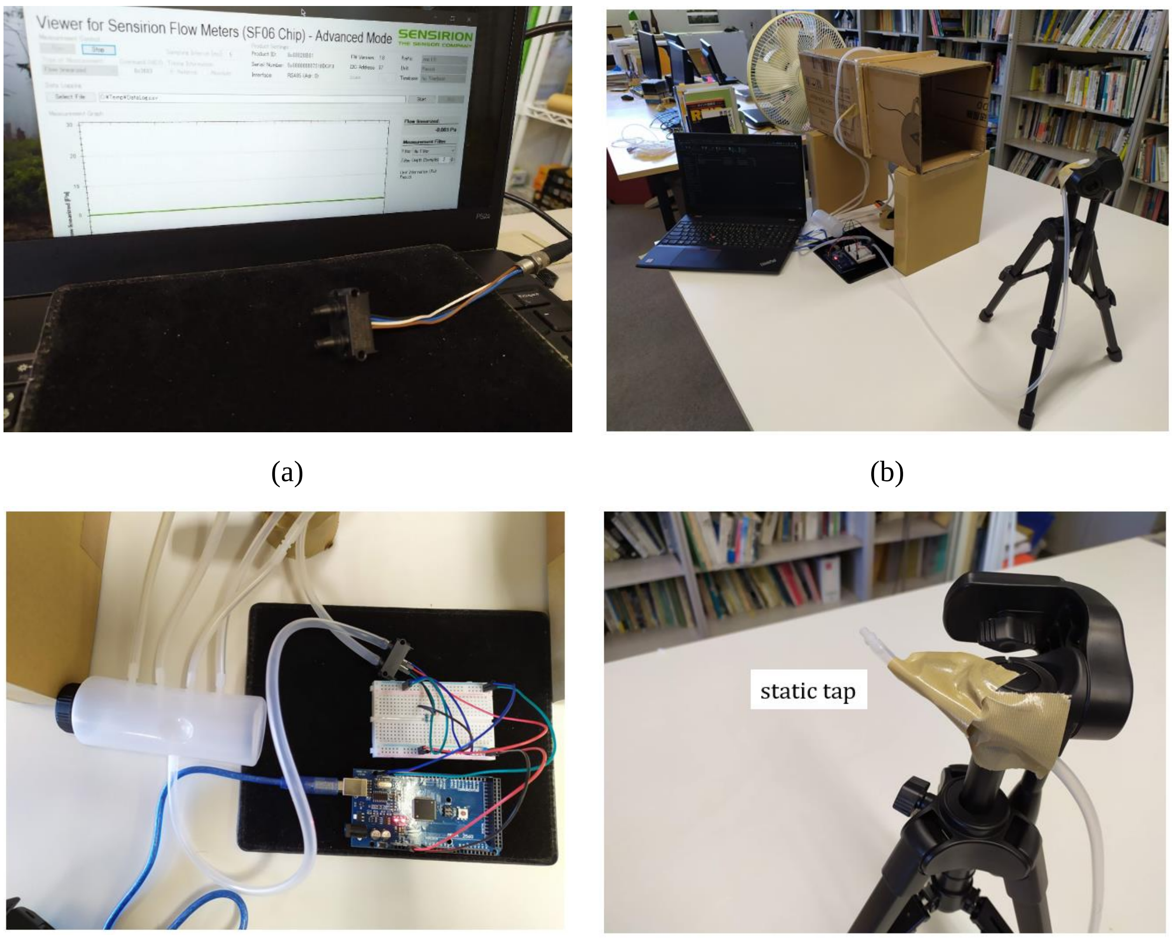
Two of the maximum ventilation points identified during the ventilation 'test 1' were taken into account to determine the position of the two extractors (see 'subsection 4.3.2'). The speeds are like those of a blower door indicated by other researchers [118]. With this device, by alternating the fans, it was possible to generate three different pressure levels (see 'table 26').

4.3. Field tests: ventilation measurement for the prototype

A pre-test and three ventilation tests were undertaken to understand the best way to collect wind data for the system. The primary concern was the pressure tap positioning (inside or outside the window frame) and the creation and test of a plenum to yield a physical average of the wind flow.

4.3.1. Specification and calibration of pressure sensors

For the ventilation tests before the construction of the prototype, four hot-wire anemometers TESTO 405i and a differential pressure sensor Sensirion SDP810 connected to a plenum were used. To test the SDP810 pressure sensors and the plenum, I adopted the EK-P5 test kit and related software provided by the manufacturer. 'Figure 62 (a)' shows the sensor connected to the kit, and the measurements plotted in real-time on the viewer. The sensor resulted particularly accurate and sensible. Furthermore, to compare the data plots coming from different wind sensing method, a small experiment was conducted. Specifically, one end of the differential sensor was connected to the plenum receiving four pitot tubes, and the other one to a static pressure tap perpendicular to the airflow (see 'figure 62 (c)'). The tubes were then inserted into the sides of a cardboard duct (200x200mm), flanked by an anemometer, and exposed to continuous ventilation coming from a desk fan (see 'figure 61 (b)'). The *Arduino Mega 2560* and the related IDE software were used to record the data.



(a) (b)

(c) (d)

Figure 61. Images from the differential pressure calibration software (a), the layout of the test and main connections (b, c), and a detail of the static tap (d).

The conditions of the experiment were the use of the fan at four different speeds considering three sessions of 8 minutes each. A single pitot tube (P_t) was used in the first session, and four pitot tubes connected to the plenum, in subsequent sessions.

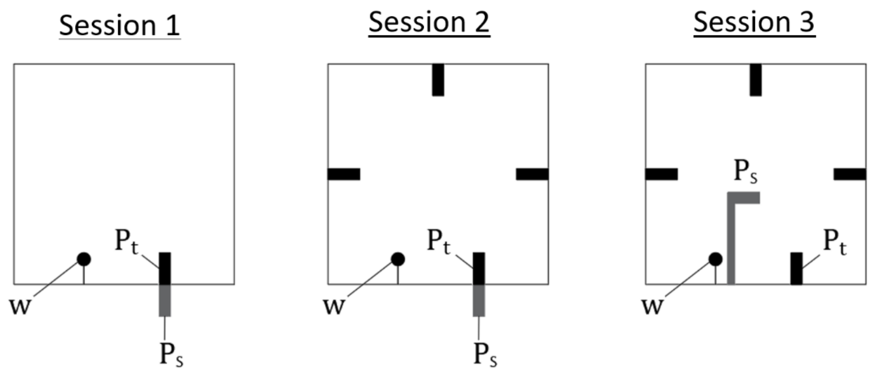
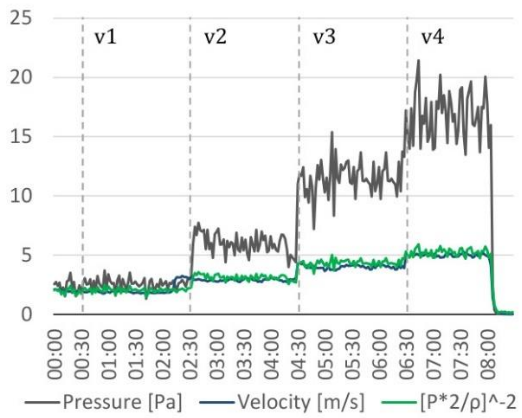
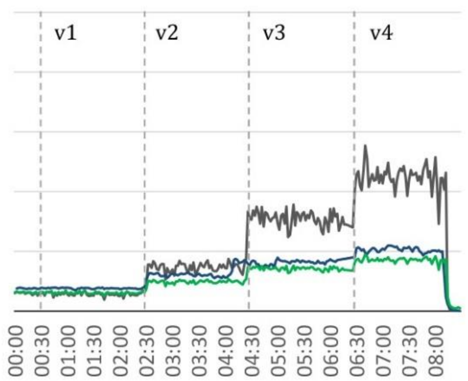


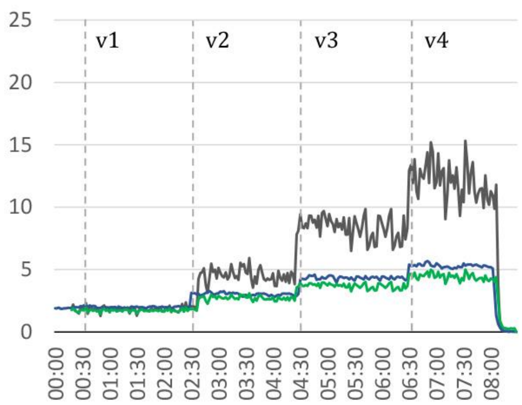
Figure 62. Duct cross-section showing the position of taps and anemometer for each session, where (*Pt*) is the pitot tube, (*Ps*) the static tap, and (*w*) the anemometer.



(s1)



(s2)



(s3)

Figure 63. Data plots from the ventilation pre-test.

The scheme in ‘Figure 62’ shows the duct section and the variation of the experiment. While the anemometer is on the same level as the pitot tube and remains fixed, the static tap (P_s) varies in position in the last session, being placed outside the duct perpendicular to the flow (see also figure ‘figure 63 (d)’). Being that the time resolution of the TESTO 405i is one recording every two seconds, the differential pressure sensor was synchronized to the same frequency to facilitate the comparison. Finally, a column of data was added to the time series, using the ‘equation (5)’ (from P_{dyn} obtaining U_{vel}). ‘Figure 63’ illustrate the results of the experiments for each session, while in grey, blue and green line are the P_{dyn}, the U_{vel} from the anemometer, and U_{vel} calculated with the formula, respectively.

The comparison gave the expected results, showing that the dynamic pressure followed the speed trends. The difference between the P_{dyn} from the formula and the speed in *s1* and *s2* was probably due to the average pressure coming from the taps and the velocity in a single point.

4.3.2. Test 1: Identification of the maximum and minimum ventilation point

‘Test 1’ helped to indicate the maximum ventilation point of the tested compartments. Thus, it was possible to compare the readings from the pressure sensors with the anemometers.

As the first step, to avoid the phenomenon of the '*vena contratta*' and to allow higher linearity of the flow passing through the two openings, special cardboard devices were created to adhere to the tested compartments. Subsequently, a mesh of 8x8 (window) and 6x16 (door) was applied to the inside of the device to divide the area into sectors and identify a snapshot of the direction and airspeed passing through the two sections via small flags. In particular, the use of the flags was suggested by the book of bioclimatic design practice and theory published by AIJ (2011), where they have been adopted to visualize the flow of air inside urban canyons [13].

Figure 64. Operationalization of the movements of the flags to produce a "snapshot" of the window and door behavior.

Before continuing on the registration phase, the movements of the flags were operationalized using a desk fan at a predetermined distance and combined with the measurements yielded by the portable anemometer (see ‘figure 64’). The following table shows the operationalization logic with the ranges and averages adopted for the test.

Table 27. Values of the movements of flags according to wind speed.

Kind of movement	Operationalization	Range [m/s]		Avg [m/s]
Slow swing	LOW	0.1	0.4	0.3
Fast random swing	MID	0.5	1.0	0.8
Continuous spinning	HIGH	1.1	>1.1	1.1

The models so composed were inserted in the compartments. Then, the movement of the flags was recorded during 1-minute video sessions (30"+30") with different opening conditions of the opposite door (0° or single-sided, 22.5°, 45°, ≃180°). The series of observations are based on four videos (1 for each opening percentage) three times per day (at 12:00, 15:00, and 18:00). Therefore, 24 videos in total (considering both openings) were analyzed (see ‘figure 65’). The test was conducted in early October.

The preliminary data regarding the door indicate that the indoor/outdoor temperature difference never exceed 1 °C (between 27.9 °C and 28.3 °C) (see ‘table 28’ (below)). For technical problems, the air temperatures of the window test were missing.

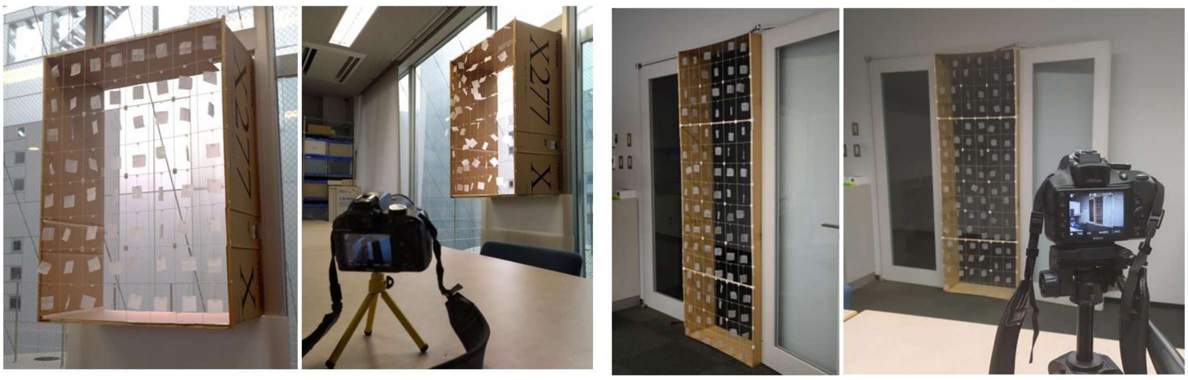


Figure 65. The special cardboard devices positioned inside the window and the door compartment.

Spreadsheets illustrating the mesh that combined airspeed and frequency with color intensity were used to visualize the results. During the experiment, it was noticed that the indoor ventilation during the sessions changed based on cycles of about 30". Therefore, the illustration below shows a half-minute subdivision.

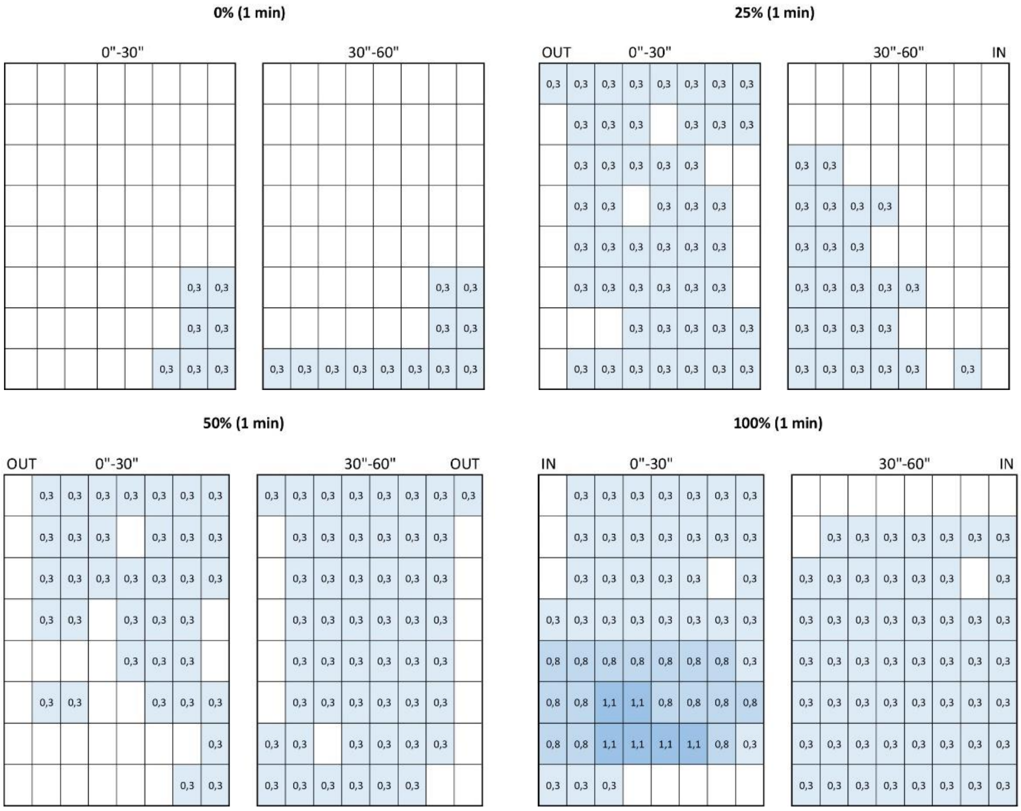


Figure 66. Example proceeding from the video analysis of the window mesh. The image shows the 15:00 session with 1- minute patterns depending on the opening percentage of the opposite door. In particular (IN) is ingoing, and (OUT) is outgoing wind.

The figure above illustrates the example of the 15:00 session regarding the window mesh. The various steps of the opposite door opening are indicated in percentage at the top of each plot.

At the end of the process, the resulting values were combined to identify the spots with higher speed and frequency. The overlapping process for the window is illustrated on the following page. Particularly, the daily sessions are displayed horizontally while the opening degrees are in vertical. On the right, red and cyan indicate the maximum and minimum ventilation points respectively (see 'figure 67'). The same process was applied for the door (see 'figures 60 (right), and 65').

By observing the results, in addition to identifying the positioning of the anemometers, the following conclusions were formulated. One aspect was that the maximum points were located at the bottom of both openings and towards the center. As expected, the lowest points were close to the edge, probably because of viscosity. The second aspect was that the percentage of the door opening of the opposite side influenced cross ventilation. Particularly, it influenced the extension of the ventilated section in a proportional way. Additionally, it was noticed that ingoing and outgoing wind produced distinct patterns. As a matter of fact, the first one provoked a more significant wind spread in the section (see 'figure 68').

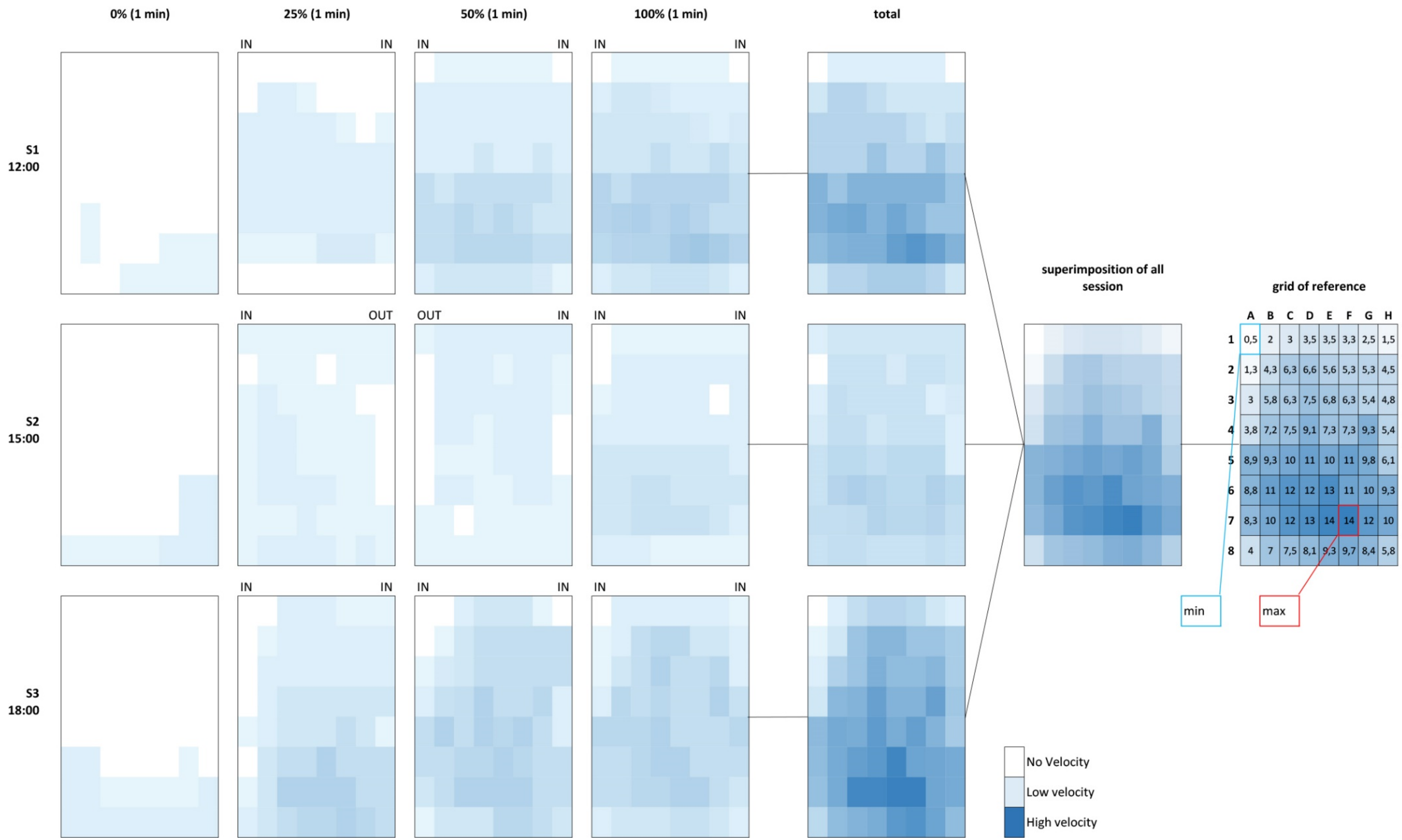


Figure 67. Overlapping process to identify minimum and maximum ventilation points (window case).

Considering the pattern of the door, the distribution on the left side probably depended on the direction of the corridor, which was perpendicular to the door and opened towards windows on the south facade. Therefore, the wind hit the inner left side of the duct and entered the room.

Concluding, the results showed where to collocate the anemometers in front of the opening. In particular, it indicated 7/8 of the height and 3/4 of the width (also for the door). The position towards the center of the window was confirmed by the literature (e.g. [118]). Furthermore, to get an idea of the ventilation capacity of the testing window, the air changes per cubic meter and by volume were calculated based on the results (see 'tables 28').

Tables 28. Room details and airflow capacity of the testing window (above), temperature measurements during the door analysis (below).

Geometric features	Dimension
Room volume	96,53 [m^3]
Door Section	1,58 [m^2]
Window Section	0,84 [m^2]

	(12:00)	(14:00)	(18:00)	Tot.
Avg. [m3/h]	798	735	1221	918
ACR [1/h]	8,3	7,6	12,7	9,5

	S1 (12:00)	S2 (14:00)	S3 (18:00)
	Air T [°C]	**Air T [°C]**	**Air T [°C]**
Corridor (start)	27,9	28,1	27,5
Exterior (start)	27,6	28,7	27,3
Corridor (end)	28,3	28,5	27,4

After the first ventilation test, two more were conducted to identify the proper position of the pressure taps inside the prototype. 'test 2' was useful for understanding the speed profile of the area in the vertical window section and for deciding the distance of the pressure taps from the inner edges. Afterward, 'test 3' helped to determine whether to place the pressure taps inside the compartment (as proposed by [50]) or immediately outside (as indicated by [118, 128, 129]).

4.3.3. Test 2: Airflow profile of the opening

The 'test 2' was carried out to evaluate the wind speed profile passing through the window. It was divided into two monitoring campaign. The first one was performed in windy weather conditions. Like the previous test, I opened the opposite door at three prefixed hours (13:00, 15:00, 18:00). While the second campaign was conducted using the DIY blower door to obtain constant measurements. The measurements were made in March.

The special cardboard device was placed in the window compartment, and the anemometers were positioned at the characteristic heights found in ‘test 1.’ Observing ‘figure 51’, the anemometer *w2* recorded the point with the maximum speed. Then, its symmetric (*w3*) was located in the upper part. The other two points were placed on the same plane varying 10, 20, or 30 mm from the cardboard device edges depending on the session. The flags around the points of interest were observed to note the wind direction during the measurements and directionality errors. In this regard, all sessions were recorded with an SLR camera. Finally, I gathered the furniture in the room, freeing the area between the two openings from obstructions (see ‘figure 69’).

For the second campaign, the DIY blower door was used during a day with no wind. At the time of the test, only an axial fan was available. Therefore, it reached a flow rate of about 50 m^3/min, generating low but constant ventilation. In both campaigns, the openings and the inner side of the curtain wall were sealed with adhesive tape, checking the infiltrations via a thermal camera.

Figure 68. Testing room with the blower door (left), and the special cardboard device with the anemometers in position (right).

Like the ‘test 1’, the monitoring schedule was divided into four steps of 2 minutes, starting from a single-sided condition up to a 180° opening. While using the blower door, I conducted a 5-minute session at a constant speed. In addition, apart from the ventilation data, it was also recorded the environmental data of air temperature and relative humidity from the RTR-576 and RTR-574 stations located inside and outside the room, respectively, communicating via a WI-FI receiver (see ‘figure 69’).

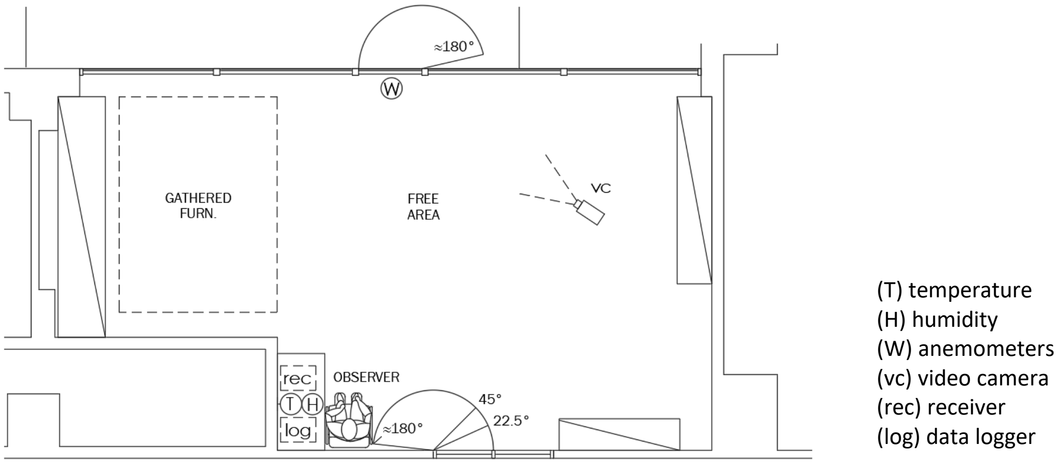
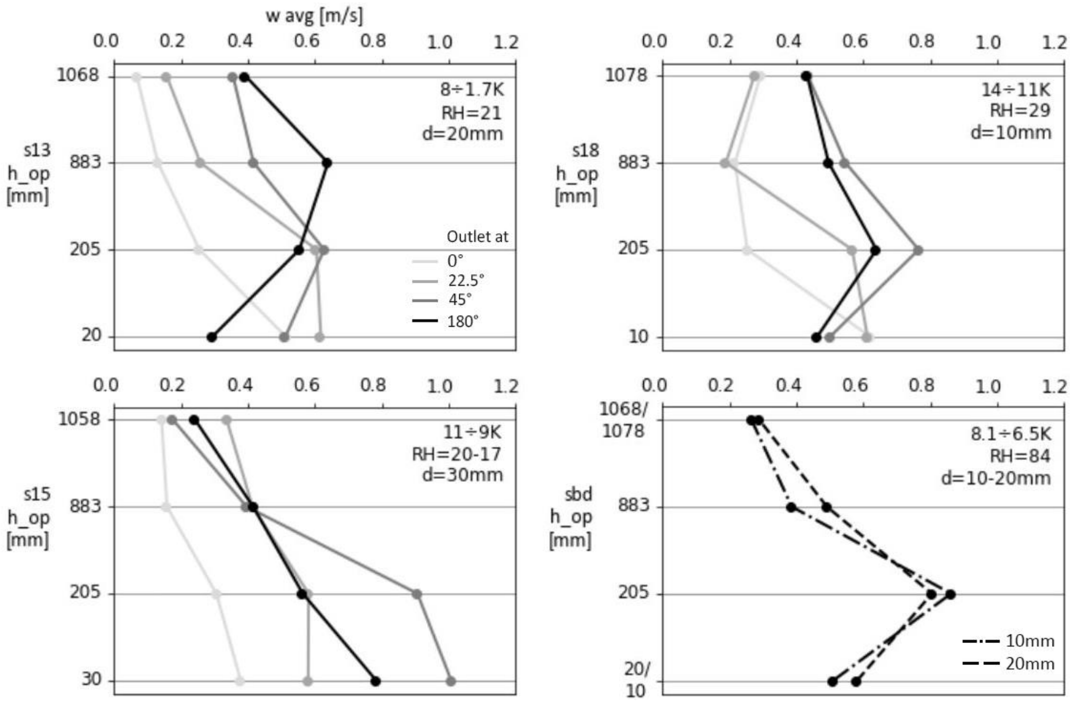
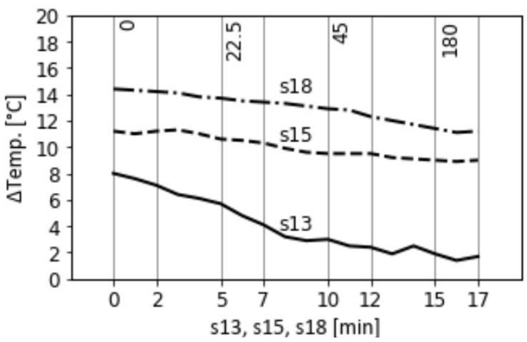


Figure 69. The layout of the room during 'test 2.' The scheme indicates the sensors and observer position during the first monitoring campaign.



(a)



(b)

Figure 70. Results of 'test 2' showing the flow profile of the testing window (a) and temperature differences during the first campaign (b).

The graphs in 'figure 70 (a)' show in the *y-axis* the distance from the lower edge of the measurement points, and in the *x-axis*, the speed measured at each altitude. In the upper right corner, there are the indoor ΔT and *RH* values at the beginning and end of the session, and the distance (*d*) from the edge of the anemometers *w1* and *w4*. Moreover, the graph in 'figure 70 (b)' shows in detail the time series of the temperature differences during all the sessions.

The results suggested that during single-sided cases, the ventilation was mainly distributed in the lower part of the section. It was not respected in *s15*, probably due to the too detached position of *w1* and *w4*. At higher opening angles, the lines tended to distribute like a 'D' shape due to the edge viscosities.

The main conclusion of the test was that the difference in the distance between 10 and 20 mm was negligible, particularly considering the results of the blower-driven experiment. Finally, the temperature difference certainly influenced the final sum of the speeds, especially in the single-sided cases.

The test was useful in clarifying certain aspects related to the dynamics of the air passing through the window. At that point, it was necessary to understand the convenience of placing the pressure taps only in the lower area, around the frame, or outside it to calculate the average of the ventilation as correctly as possible, respecting the constraints given by design. This aspect was addressed in 'test 3' and after the realization of the prototype body.

4.3.4. Test 3 - First measurements with pressure taps

Based on the positive outcomes of the experiment discussed in 'subsection 4.3.1', it was adopted the same methodology but at a larger scale using the special cardboard device. Particularly, observing 'figure 71' (above right), I used the SDP810 differential sensor connected to a plenum at one end, and to a static tap at the other, which was inserted flush to the inside of the lower face of the device. The preparation of the test followed the same procedures adopted in 'test 2', with the difference that only the blower driven phase was performed.

The test was organized into two sessions (*s1*, *s2*) by changing the configuration of the components (see 'figure 72'). Specifically, *s1* had four taps located at the bottom, while in *s2*, they were inserted in all the sides of the device.

Three anemometers (*w*) were placed alongside the pitot tubes (P_t), while the fourth (w_{max}) was located at the point of maximum ventilation. Finally, the data monitored by the SDP810 were visualized by a computer via the serial port and the EK-5 software.

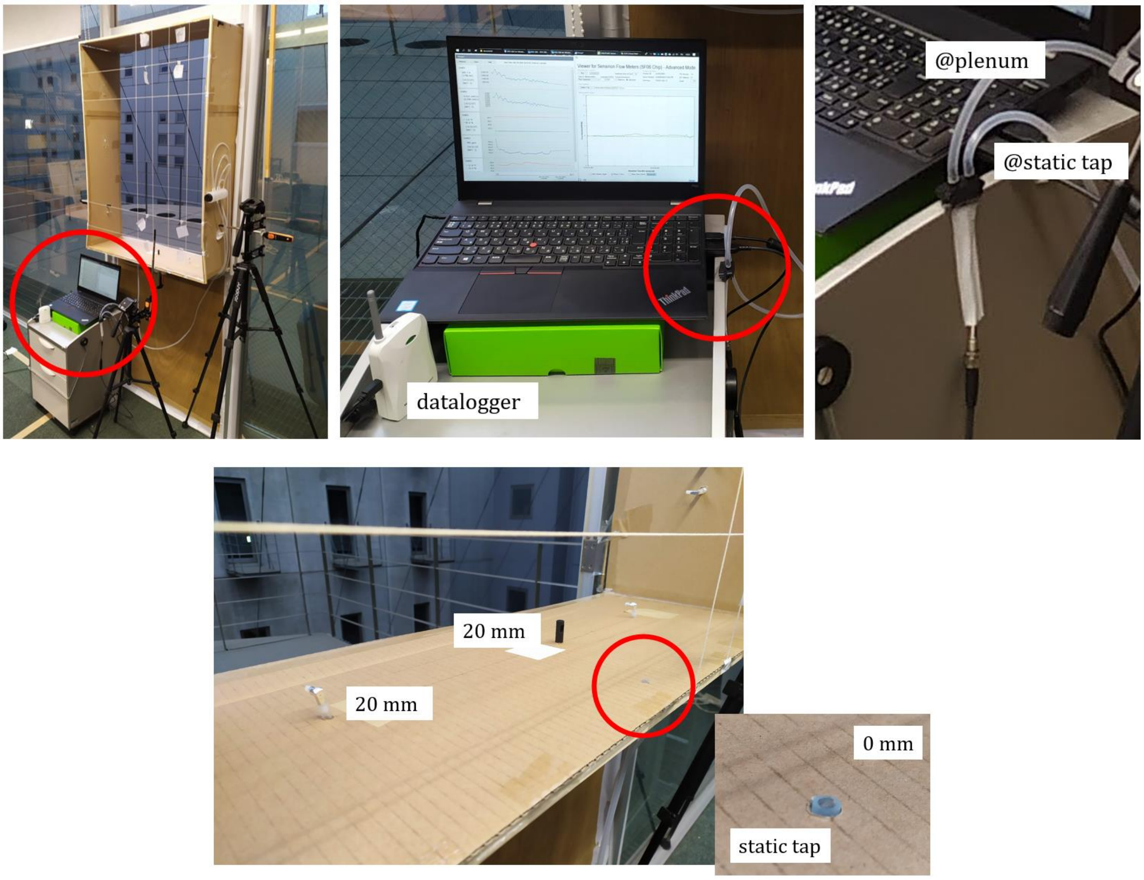


Figure 71. Pictures of the preparation of 'test 3'. General images and differential sensor connections (above), detail of the position of the tap inside the special cardboard device (below).

The boundary conditions and the sensors adopted for the test were similar to 'test 2' for the blower driven phase (see 'figure 69' as reference). The difference in indoor and outdoor temperature and relative humidity were also similar (respectively 6.5K ÷ 7K and RH 85%). Finally, the testing schedule involved the increasing of the fan speed of the DIY blower door in successive steps of 2 minutes each, starting from 1) Off, 2) Low, 3) Mid, and 4) High, and again Off.

The time series in 'figure 73' visualize the data from the tests. The airspeed is shown in the vertical axis, while the four progressive steps of depressurization are indicated horizontally. The dotted line is the maximum values recorded by w_{max}, while the continuous blue and green lines are the average speed of all the anemometers and the velocity obtained from the equation (5), respectively.

The results showed a constant increase in the turbulence of the average pressure values (especially in *s1*). While the dynamic pressure in *s1* was generally in line with the trend of speeds, in *s2*, there was an evident gap with p_{dyn} and the velocities, especially observing the behavior of the average values. In *s2*, the expectation was that the distribution of the pitot tubes around the compartment would generate results compatible with those measured by the anemometers. Nevertheless, it was not possible to explain the reason for the outcomes. However, after the three preliminary tests, I passed to the prototype construction and tested the opening behavior again. For this purpose, the design permitted to switch the position and direction of the taps. In the following text, the prototype realization and assessment are discussed.

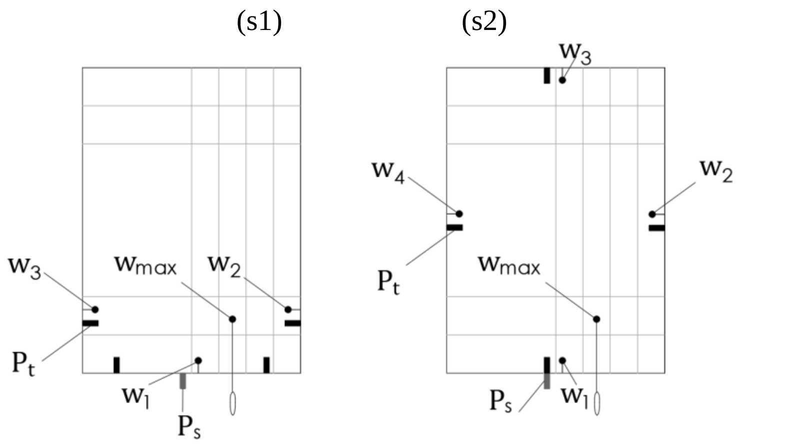


Figure 72. Cross-section of the special cardboard device showing the position of the taps and the anemometers in "test 3", where (*Pt*) is the pitot tube, (*Ps*) the static tap, and (*w*) the wind sensors.

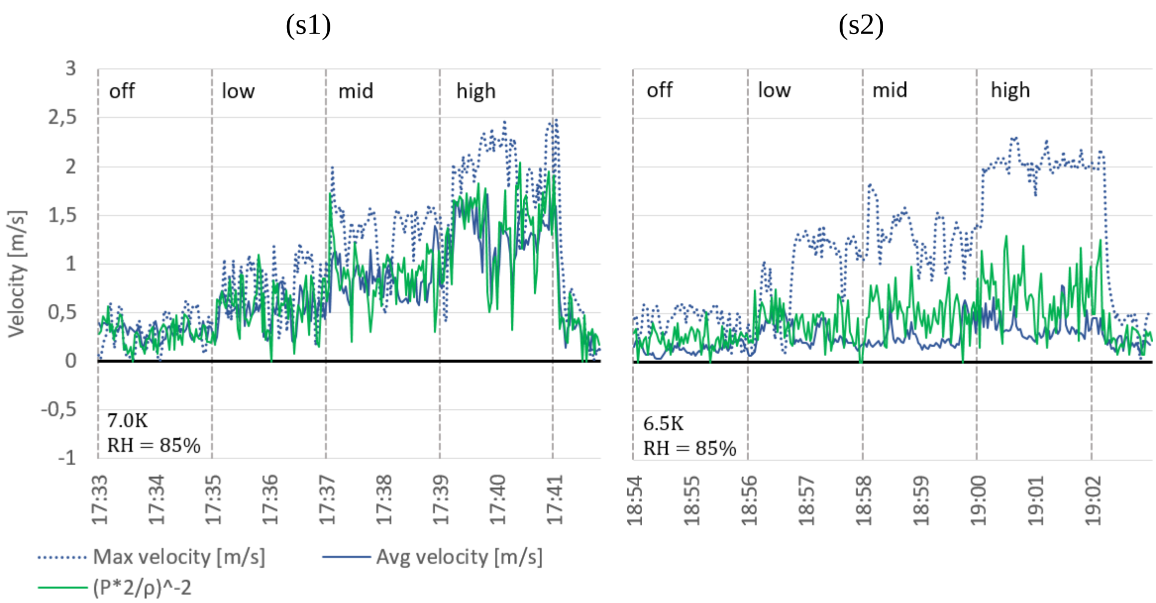


Figure 73. Results of 'test 3' highlighting the different measurements according to taps position.

4.4. Description of the LBVW prototype

The current section introduces the prototype of the LBVW system, indicating what the main components and the connections are. Then, it is illustrated how the various modules communicate between them. Afterward, it is described the test that demonstrated the prototype capabilities on sensing the environment. Eventually, it is explained how the prototype visualized comfort/discomfort signals and the detailed information proposed for the system.

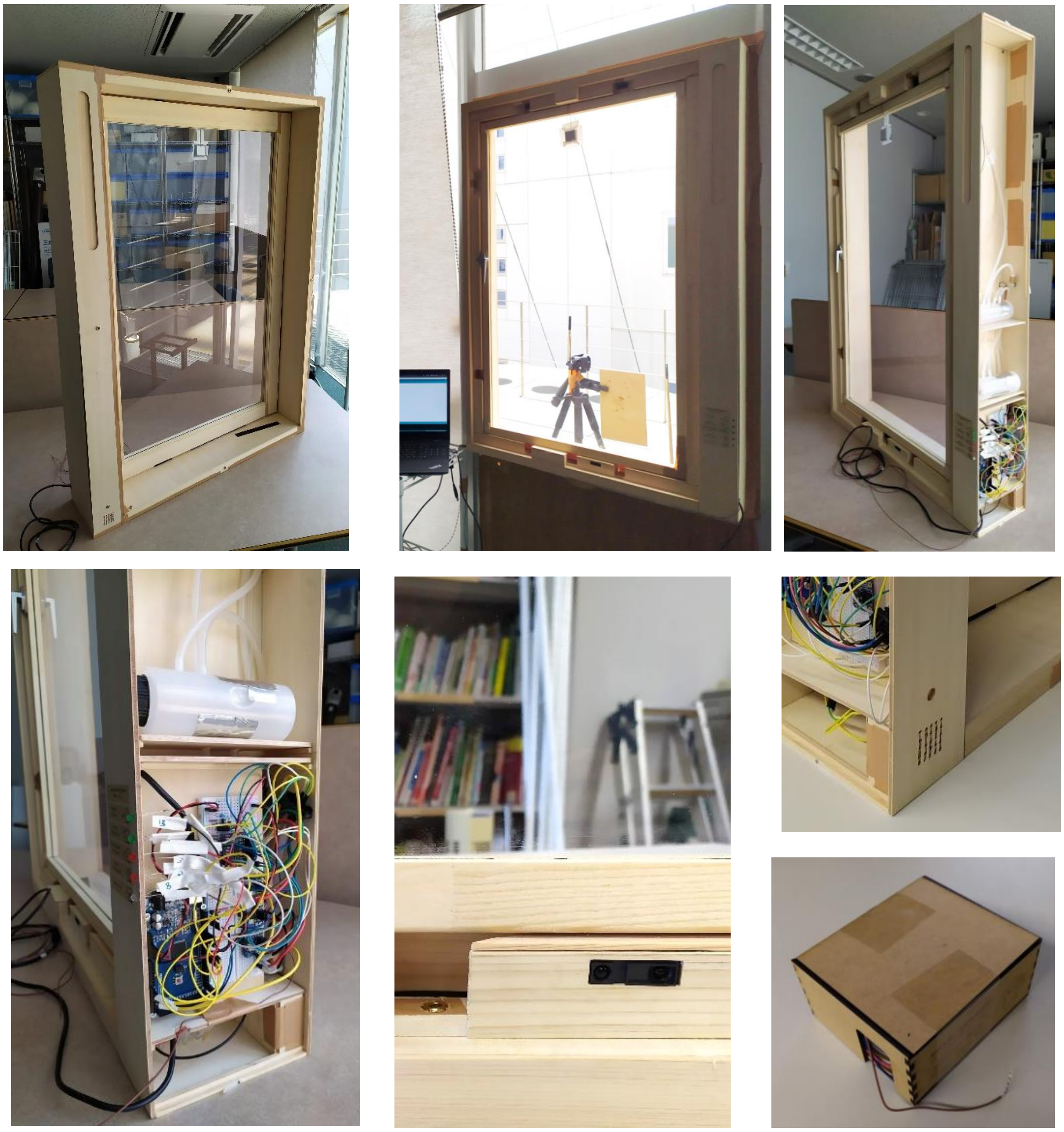


Figure 74. The main window prototype (above), details (below left and center), and the image of the wall device (below right).

4.4.1. The realization of the prototype

The first version of the LBVW prototype followed the design showed in 'figure 46'. It was made of plywood and Plexiglas and adopted a control system that manages the sensor network and a plenum connected to an array of pressure taps that can be placed in different positions. The final location of the pressure taps was decided after the conclusive ventilation test, as described in the following section. Regarding the other components, the controls were located on the right side of the opening casing (see 'figure 74 (above right)'), while the position of the environmental sensors variated according to the function.

In the first place, user presence sensors were located on the inner side, integrated into the frame at the bottom (see 'figure 74 (below left)'). The door distance sensor was in the middle-lower part of the frame (facing outwards) to detect the door movements ('figure 74' (above center)). Furthermore, the location of outdoor air temperature and humidity was located in the control compartment near the PCBs, insulated by polyester foam, and connected to the outside via small holes on the lower part of the exterior sash. Finally, the thermocouple measuring the temperature of the glass was installed on the above portion of the window.

The prototype of the wall device resulted in a small case opened to one side to allow to put the thermocouple directly on the surface of the opposite wall, and to facilitate the measurement of the indoor data (see 'figure 74' (below right)). In specific, this device permitted to locate the CO_2 and *RH* sensor away from the window to avoid compromising the data. Likewise, more wall devices could be put on the other walls to increase LBVW system accuracy.

4.4.2. Assembly of the system modules

The sensing module was realized with the components listed in 'table 29'. Most of the sensors exploited digital technologies, while others were analogical or signal converters. The K-30 is the same sensor integrated into the RTR-576 probe used for testing, and it is based on NDIR technology. The GP2Y0A21 distance sensor measures the lapse of time traveled by a light wave in and out generated by an Infrared Emitting Diode (IRED) towards the target surface. Finally, the Sensirion SDP810 pressure sensor uses technology based on the CMOS silicon chip, and the thermal-flow-through operating principle that detects the differential pressure through a heater and the temperature difference inside a microchannel.

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(this figure is concealed due to possible conflicts with a patent application)

Figure 75. Connection of the SDP810 sensors to plenum and taps inside the control compartment.

The connection of the PCB to the network followed the logical levels and the I2C communication protocol. First, to use the sensors at full capacity, the connections were divided into two separate logic levels (5V and 3.3V). In the case of the wall device, it only adopted the 5V logic. Secondly, most of the sensors utilized in the prototype were based on the Inter-Integrated Circuit I2C Serial BUS system. It is a data exchange protocol between IC sensors and microcontrollers (devised by Phillips). The wire connections consist of two communication lines, a Data Line (SDA) and a Clock Line (SCL) and the electrical circuit with Voltage input (Vcc) and ground (GND). Usually, the sensors are placed serially as ‘slave’ and dependent on a ‘master,’ which in this case is a Printed Circuit Board (PCB). Additionally, for the PCB to recognize the sensor, the address must be entered in the programming phase.

‘Figure 76’ shows the sensors connected to the relative PCBs. In the case of the central system, the thermocouples were connected to two identical I2C Converters having the same address. To overcome this issue, I used a TCA9548A breakout Multiplexer from Adafruit. In particular, it behaved modularly like a 'gatekeeper,' with its address (default is 0x70) and gave the possibility to manage up to eight I2C per module using an alternative recognition code (*tcaselect*) and indicating a number to 0 to 7 according to the position to be recalled.

All the I2Cs of the central window were linked to the Multiplexer to maintain order in the connections and coding. Finally, the two distance sensors GP2Y0A21 were plugged in the analog ports of the PCB.

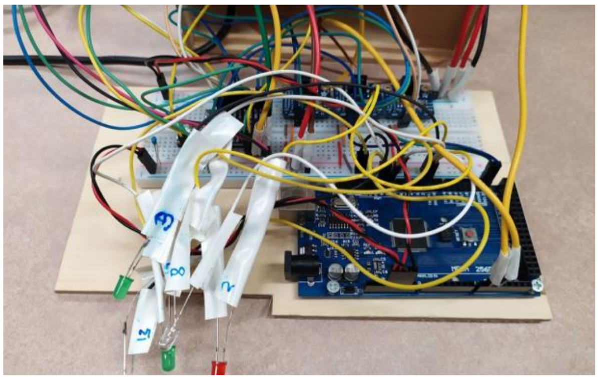
The wall device was connected to a Bluetooth Shield HC-06 to allow communication with the central controller. It worked with *Tx* and *Rx* output channels (to be connected inverted to the PCB). Furthermore, it had an integrated breakout board for levels from 3.6 to 6V but required a voltage divider for the *Rx* channel (which only received 3.3V). As a reference for the sensor connections, see ‘figure 77’ (on the next page) and ‘figure 55 (above)’.

Table 29. List of components of the sensing module for both the devices.

Name	Parameter	Vcc [V]	Technology	Range	Accuracy
Texas instruments GP2Y0A21YK0F	Proximity	-4.5 to 5.5	IRED (Analogue)	10 to 80 cm	-
Adafruit MCP9600	Temperature	3.3 to 5.5	Thermocouple type T amplifier (I2C Converter)	-200 to 400 °C	±0.06
Texas instruments HDC1080	Humidity Temperature	2.7 to 5.5	Integrated Circuit (I2C)	0 to 100% -40 to 125 °C	±2% ±0.2 °C
CO_2 Meter K-30	CO_2	5.5 to 9	NDIR (also I2C)	0 to 5000 ppm 0 to 10000 ppm	± 30 ppm (± 3 %)
Sensirion SDP810	Differential pressure	3 to 5.5	CMOS (I2C)	-125 to 125 Pa	0.08 Pa
Bosch BMP180	Barometric pressure	1.8 to 3.6	Integrated Circuit (I2C)	300 to 1100 hPa	±1 hPa

4.4.3. Calibration and positioning of the sensors

Prototype sensors calibration followed the method adopted for the probes and monitoring stations used in the previous tests (see ‘subsection 2.3.4’). In specific, I found that the K-30 reduced readings of 50 ppm compared to the RTR-576 and typical outdoor values. Additionally, testing the RH sensor with the calibration kit at 62% resulted in +6% above the normal. Both readings were manually corrected inside the *Arduino* code. On the other hand, thermocouples inserted in a mix of water and ice reached a value of -0.12 °C, respecting the accuracy range.



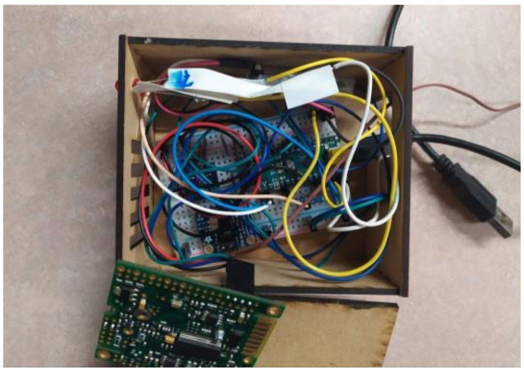


Figure 76. Photos of the circuits of the prototype: inside the main window (left), and the wall device (right).

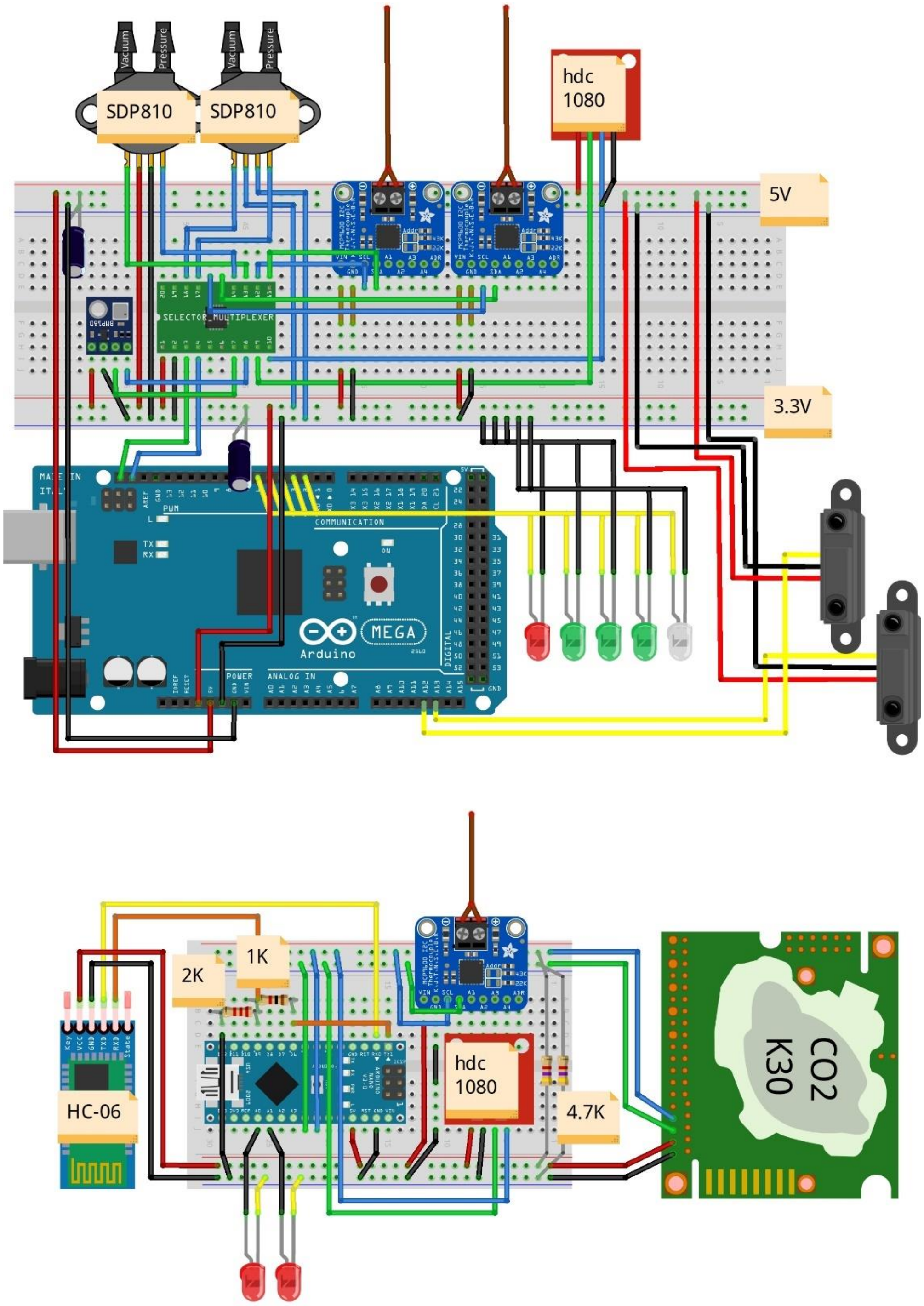


Figure 77. Connection diagram of the circuits for both the devices. The monitoring station inside the main window (above) and the wall device (below).

Particular attention was paid to integrate the door distance sensor to the window opening. I chose to place it in the horizontal half of the upper frame (30 cm from the door hinges) so that it measured linearly the cathetus of the triangle created by the door during opening (see the scheme in ‘figure 78’ on the next page). Furtherly, d_x determined both the 'speed' and the gradation in the values of d_y and the maximum distance $d_{y,max}$ beyond which the sensor measured + ∞ (random values, recognizing a total opening). During the positioning, it was noted that by placing the sensor 10 cm from the axis of the hinges, a value of d_y = 10 cm described a door already at 45° of opening. At 30 cm instead, by sacrificing accuracy at wider apertures ($d_{y,max}$ is 52 cm instead of 59 cm), more gradual measurements were obtained, improving the smoothness of the interaction. 'Table 30' shows the two cases compared up to a value of 20 cm and the calculation of A_{eff} based on d_y indicated by the sensor. Eventually, regarding the sensor, a change in measurements was detected near objects less than 9 cm away. This limit was considered during the assembly of the prototype.

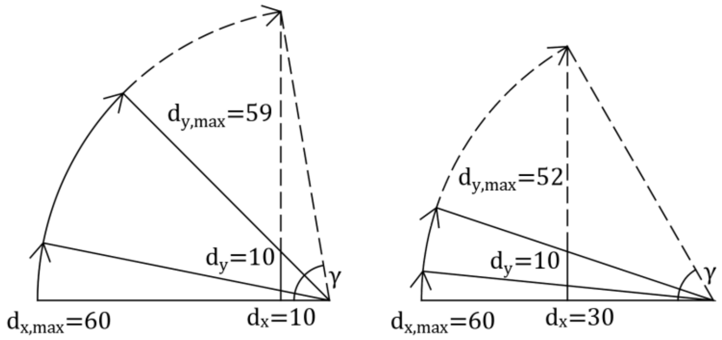


Figure 78. The impact of different distance sensor location on the opening geometry.

x [cm]	y max [cm]	y [cm]	α [degr]	A eff [m 2]	x [cm]	y max [cm]	y [cm]	α [degr]	A eff [m 2]
10	59	0	0	0,00	30	52	0	0	0,00
		1	6	0,10			1	2	0,03
		2	11	0,19			2	4	0,07
		3	17	0,26			3	6	0,10
		4	22	0,32			4	8	0,13
		5	27	0,36			5	9	0,16
		6	31	0,40			6	11	0,19
		7	35	0,42			7	13	0,21
		8	39	0,44			8	15	0,24
		9	42	0,46			9	17	0,26
		10	45	0,47			10	18	0,28
		11	48	0,48			11	20	0,30
		12	50	0,49			12	22	0,32
		13	52	0,49			13	23	0,33
		14	54	0,50			14	25	0,35
		15	56	0,50			15	27	0,36
		16	58	0,51			16	28	0,37
		17	60	0,51			17	30	0,39
		18	61	0,51			18	31	0,40
		19	62	0,51			19	32	0,41
		20	63	0,52			20	34	0,41

Table 30. Results of different interactive experiences given by the distance sensor position.

4.4.4. Conclusive test: collecting environmental data with the prototype

A conclusive test was conducted to demonstrate the capability of the LBVW prototype in collecting wind and other environmental data. At that time, I variated the configuration of pressure taps and compared their measures with four anemometers. For this purpose, the prototype accommodated six pitot tubes in the window frame, and their position could be switched using the four points located at the centerline of the external sash (see 'figure 79' (above)). Thus, it was possible to test the behavior of the prototype with different configurations and choose the most suitable for the case. 'Figure 79' (below) shows the collocation of the prototype in the testing room compartment.

Figure 79. Detail of the pressure taps in the outside position (above left) and integrated into the frame (above right). The collocation of the prototype inside the testing room (below).

The test followed the same methodology of 'test 3' (see 'subsection 4.3.4'). The difference was in the first two steps. In the first step, the window was closed, while in the second one, the window was open at 90°, which was the maximum achievable given the geometry of the compartment. Also, the monitoring sessions were like 'test 3', with the possibility of switching to the external position of the pressure taps (see 'figure 80'). Mainly, *s1* measured the lower part with the taps integrated into the frame, *s2* extended the measurement to all the inner sides, while *s3* was performed with pressure taps ($P_{t,e}$) collocated outside.

In the first two sessions, the tap P_s acted as a static tap, while in the *s3*, it was considered as a reference of the internal pressure. Although the placement of the latter in a more protected position could have increased the accuracy of the results, it should have been integrated into the prototype casing without accessing the internal part of the parapet as recommended by literature [118]. In addition, the risk was to create a 'pull' effect if placed parallel to the flow.

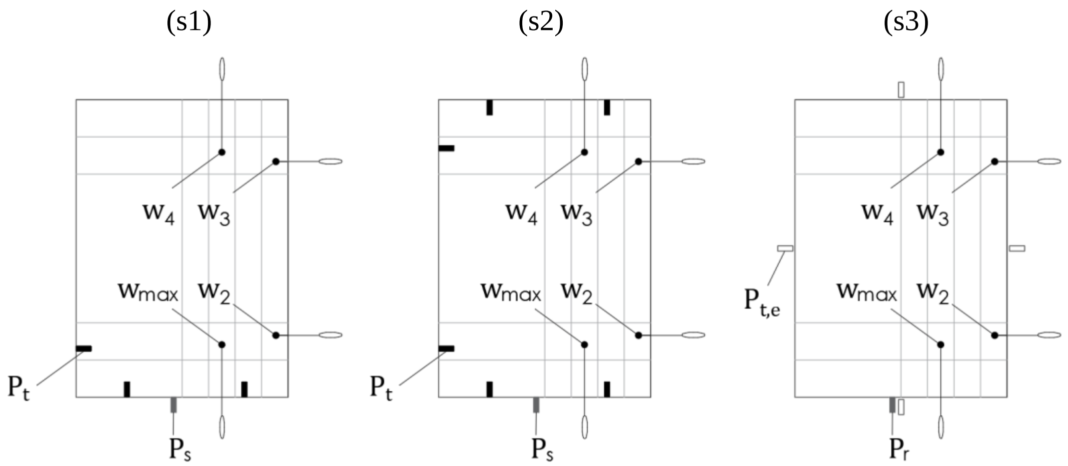


Figure 80. Cross-section of the prototype during the three sessions of the test, where (*Pt*) is the pitot tube, ($P_{t,e}$) the exterior taps, (*Ps*) the static tap, (P_r) the reference tap, and (*w*) the anemometers.

The boxplot in 'figure 81' shows the data of the three sessions. Each session was divided into five steps based on the position of the window and the level of depressurization created by the DIY blower door. In the graphs, the upper left corner shows the differences in the internal humidity and temperature between inside and outside. The indoor temperature of the experiment followed the trend of the external conditions and reached maximum temperature differences of 6K. The external relative humidity fluctuated between 45% and 32% with a difference compared to the internal values between 20% and 5%. As for 'test 3', the blue dotted line indicates the speeds measured in w_{max}, the solid blue line is the average, while the green line is the calculated velocity from P_{dyn}.

Generally, the results showed an essential distinction in the velocity trends between the measurements conducted with the integrated or external *Pt*. Notably, the outputs of ‘test 3’, where the taps were integrated into the frame, were confirmed with the increase in turbulence starting from medium-high depressurization levels.

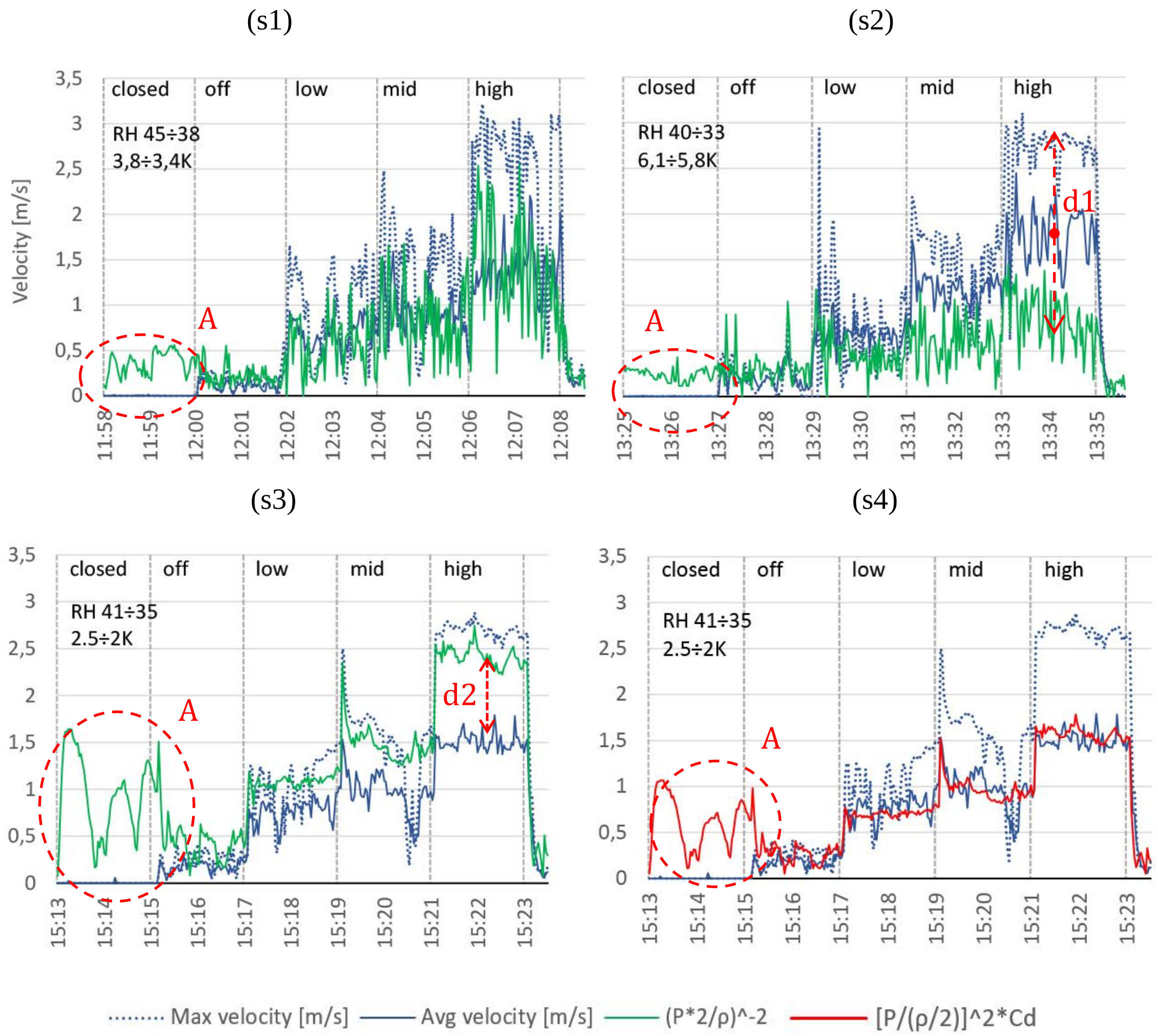


Figure 81. Ventilation measurements performed with the LBVW prototype. Results obtained with integrated taps (s1, s2), with outside taps (s3), s3 performance corrected by *Cd* (s4).

By observing the trends of the curves in detail, in *s1*, P_{dyn} was similar to w_{max}, with a slight underestimation of the w_{avg} values starting from the medium-high values. In *s2*, the apparent discrepancies of values between P_{dyn}, w_{avg}, and w_{max} were confirmed, especially at high speeds (see arrow *d1*). Then, in *s3*, the turbulence decreased with higher linearity of the data, and P_{dyn} followed the trend of average speeds accurately enough.

Some anomalies in pressure detection were identified, looking at the first part of the time series (circles ‘A’). In *s3*, when the *Pt* were external, the sensor recognized pressures produced by the wind on the facade during the closed position of the window. Compared with the same area in *s1* and *s2*, the detected speeds were most likely due to the poor airtightness of the prototype, which was not compatible with a standard window. Finally, despite the general coincidence of P_{dyn} and w_{avg} in *s3*, a gap of about 1 m/s was generated at higher speeds (see arrow *d2*).

According to the results of the test, the session *s1* was the most accurate in measuring the maximum speed of the air passing through the window. The fact was quite intuitive if we consider that the average recorded by P_{dyn} in the lower portion of the opening was physically around w_{max}, carefully respecting the tendency of perceived changes. Subsequently, the P_{dyn} in *s2* was very close to the w_{avg} values but lost accuracy, starting from the average speeds. While in *s3*, the average results were almost compatible, but there was a false pressure detection when the window is completely closed.

To conclude, considering the output in its entirety, the *s3* was the closest to the prototype objective, which was the analysis of average speed with sufficient levels of prediction. Additionally, looking at *s4*, the value coming from the pressure taps was corrected, multiplying them by the discharge coefficient (C_d = 0,65). In the graph, the red line coincides with the average calculated by the anemometers, and the gap in *d2* is sharply reduced.

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Figure 82. Variation of sensor configuration according to the window position.

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As already mentioned, changing the location of P_r paying attention to the integration inside the device, and variating C_d according to the opening angle, could furtherly increase the accuracy of the response. This aspect could be implemented when the design of the window will be at a more detailed stage. Concluding, the conclusive test demonstrated that the prototype generally yielded accurate data referring to the outside and crossing wind flow.

Regarding the collection of the other environmental data, 'figure 83' illustrates the data loop obtained by the window and the wall device during the test. In this case, the prototype demonstrated the ability to detect the other environmental parameters necessary for the LBVW system to function correctly.

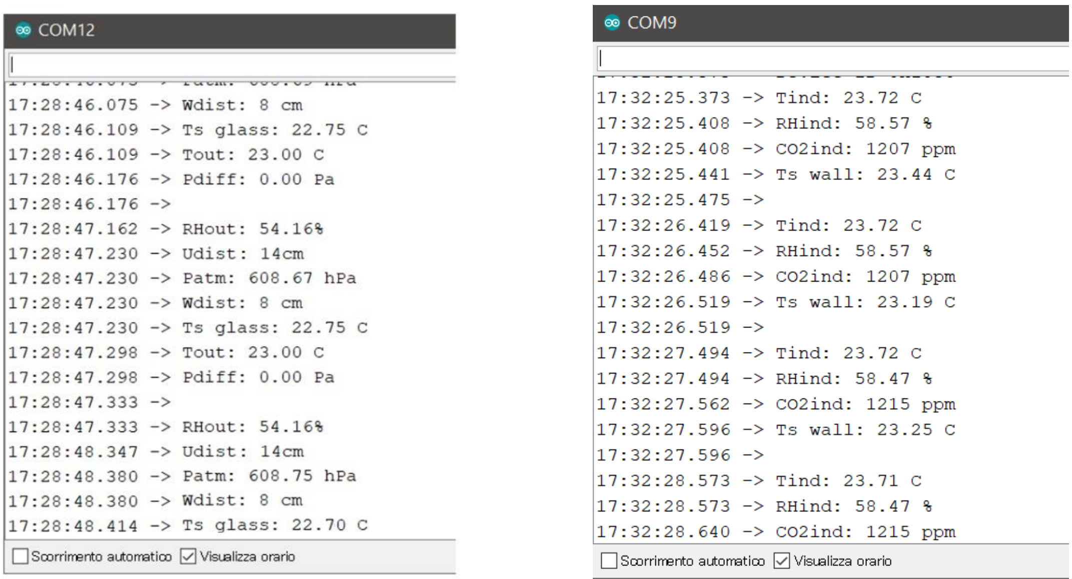

Figure 83. Loop of data provided by the main window (left) and the wall system (right).

4.4.5. UI and signalization of the prototype

The hardware and software limits of the prototype required a series of simplifications on the interface simulation. As previously explained, these limits came from the *Arduino* board used both as a Monitoring Station and a Control Center, which reduced the possibility of more agile programming. Specifically, the limits involved the ambient signals and the displayed information of the UI.

First, the ambient signals were replaced by colored LEDs. Specifically, the red LEDs indicated discomfort messages, while the green ones the comfort opportunities (see 'figures 84, 85').

In ‘table 31’, the meaning of the signals is described in detail. The ideal condition was to place all the LEDs next to the window. However, due to connection limits between the two devices, the discomfort signals provided by the wall device were shown separately. Consequently, the "*Inside is uncomfortable*" message was separated from "*Indoor humidity is high/low*," which became part of the LEDs of the wall device (see ‘figure 85’ and ‘table 31’).

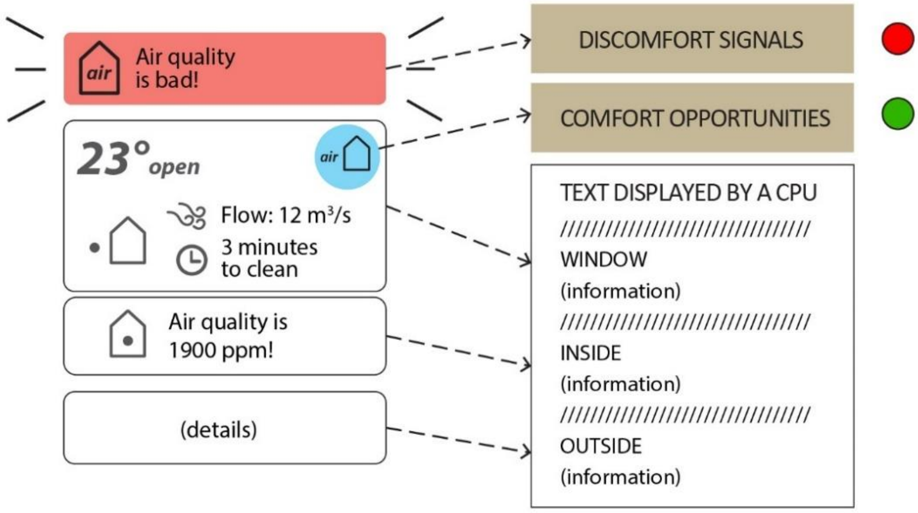

Figure 84. Adaptation of prototype signals to simulate the UI.

Table 31. Description of the signals (led lights) proposed for the prototype.

Discomfort warnings		Description
INSIDE IS UNCOMFORTABLE °C	red	It **turns on** when the operative temperature is outside the comfort zone. It **turns on** also when humidity is high/low.
AIR QUALITY IS BAD air	red	It **turns on** when inside CO_2 is more than 1000 ppm.
Comfort opportunities		**Description**
AIR QUALITY IS GOOD air	green	It **turns on** when there is no pollutant outside, and CO_2 is good (for the prototype it is always on), indicating the possibility to open for air change.
WIND IS COMFORTABLE °C	green	It **turns on** when the outside temperature is comfortable OR if the wind is not calm (in Summer), indicating the possibility to change indoor comfort conditions.
OUTSIDE HUMIDITY IS OK	green	It **turns on** when the outside humidity is between 30% and 70 %, indicating the opportunity to regulate indoor humidity based on outdoor conditions.
Other signals		**Description**
DISPLAY IS ON! ON	white	It **turns on** when the user is in front of the window. It is a simplification to permit the user to recognize when the information will appear on the glass.

Figure 85. Pictures of the comfort/discomfort LEDs inserted in the wall device (left), and on the internal sash of the main window (right). A white led was added to simulate when the display was on.

Second, a laptop computer near the central window and connected to it via the serial port was used to view the data provided by the system. Then, a smartphone visualized the information coming from the wall device via Bluetooth protocol. However, the displayed information had the same organization of the designed interface and was shown at two-second intervals, to allow time for the system to 'scroll' the text and the user to read (see 'figure 84'). Additionally, 'table 32' illustrates the structure (left column) and the alternatives inserted in the algorithm to describe the change in conditions (right column). As a default, the detail part showed the external temperature and relative humidity (and the differences compared to the indoor values).

Table 32. Serial data yielded by the computer screen and the list of alternatives inside the script.

General structure	Alternatives
//////////////////////////////////	
WINDOW	
Opening angle: 23°	Open/Closed
Flow: 23 m3/s	Wind speed
//////////////////////////////////	
INSIDE	
Air quality is good (500 ppm)	good!; bad!; very good!/bad!;
Minutes to clean: 3	-
Your room is slightly hot	comfortable; slightly hot/cold; hot; cold; very hot/cold
Humidity is OK!	OK!; slightly low/high; low; high; very low/ high
//////////////////////////////////	
OUTSIDE	
Wind is breezy & fresh	calm; gentle; breezy; strong; & pleasant/warm/fresh/hot/cold
Humidity is OK!	OK!; slightly low/high; low; high; very low/ high
Weather will be warmer	stable/colder/warmer
//////////////////////////////////	
DETAIL T: 23° (*+2*) H: 45%(+20)	T indoor; T outdoor; T operative; T comfort; Barometric pressure; Humidity outside; Humidity inside; Wind speed.

4.5. Case Study II: Interaction and learning with the LBVW window

The purpose of "Case Study II" was to give an idea of the initial learning process of the LBVW concept by having a group of volunteers use the prototype. Although the participation and the consequent variety and number of samples were reduced due to the *Covid-19* diffusion control, the test was useful to understand how people respond to the information and as an initial step towards future experiments.

4.5.1. Preparation of the campaign

Based on the hypothesis proposed at the beginning of the research, the window was designed to trigger a long-term learning process in favor of internal comfort, indoor air quality, and the consequent reduction in energy consumption. The test hypothesis was that the prototype could trigger an initial learning process using the window. Particularly, the prototype:

- Could inform the user of discomfort situations, and the comfort opportunities given by the external environment;
- Could show information for adequate ventilation, balancing comfort situations with the need for air exchange.

Therefore, the main objectives of the campaign focused on three points:

1. Understanding if the comfort/discomfort messages agreed with the testers' votes;
2. Understanding if the indoor/outdoor information matched the tester's feelings and if they had an impact on their opinion;
3. Understanding if the information had an impact on a given air change task, as the first step towards the learnability of the system.

The test adopted a longitudinal sampling with the participation of a small group of subjects for 55-60 minutes. The procedures consisted of a monitoring and survey campaign aimed at involving the testers to use the prototype inside a semi-controlled environment (like 'Case Study I'). Additionally, their votes and impressions on the information displayed and learnability of the system were collected. In this context, the volunteers were tested individually by alternating hands-on approaches with a survey divided into four moments, one for each phase of the case study (for the survey model see 'Annex B'). The following text lists the four parts of the test:

- ***Part 1*** – Explanation and preliminary questions (20’) - The tester sits and receives the first instructions;
- ***Part 2*** – Exploring the prototype for comfort (15’ or more) - First approach the prototype;
- ***Part 3*** – Task: Reaching an adequate ventilation time (10’) - Second approach;
- ***Part 4*** – Conclusion: Learnability and satisfaction using the system (10’)

The four-part sequence was intended to allow the tester to discover the system gradually and to divide the experiment into clear topics.

During ‘part 1’, the examiner introduced the LBVW system to the tester, with the help of an infographic. In particular, the purpose and system, the data elaboration, and the visualization system were described in detail. Subsequently, it was showed how to use the prototype and listed its limits. At the end of the explanation, the tester filled the first part of the survey, consisting of introductory questions related to the window use, as well as giving information on *clo* levels. Additionally, the initial explanation time was utilized to make the volunteer used to the testing room microclimate.

For the survey in ‘part 1’, the questions investigated the traditional approach to ventilation. Mainly, they referred to the factors that drive the use of the window and what are the ventilation practices usually adopted by the testers. Finally, the survey asked about the tester’s state of comfort, the sensations felt at that moment, and his/her predictions on the external climate by keeping the window closed. In other words, based on ‘Case Study I,’ the focus was to describe the tester's level of awareness of the internal and external environmental parameters (humidity, temperature, and air quality).

‘Part 2’ was dedicated to clarifying the volunteer's response to the messages of comfort, discomfort, and detailed information. At the same time, the system's ability to predict tester’s state and the main environmental parameters were assessed. In this phase, there was a first 'hands-on' session, where people freely interacted with the window.

During ‘part 2’, the volunteer was indicated to respect the following steps (referring to the Learning-By-Doing approach):

Step 1. Wait for the discomfort messages;

Step 2. Get in front of the window and wait “display is on” signal;

Step 3. Read the comfort signals indicated by the window;

Step 4. Check the information on the display;

Step 5. Operate the window freely (take as much time as you want);

Step 6. Leave the window open and sit down.

In the first four steps, the tester was asked to check the congruence of his/her sensations and comfort votes with the information displayed by the window. Then, before opening, the observer asked to describe personal feelings and judgment on the external climate a second time. Thus, it was possible to identify the impact of information on their opinion as an initial learning process. Eventually, the volunteer finished the questionnaire indicating issues and curiosities encountered during the first use of the prototype.

‘Part 3’ consisted of a small ventilation task to understand the learnability of the system in practice. This phase maintained the same steps as the previous one, while the survey was completed post-task. In specific, the objective was to resolve the "*Air Quality is Bad!*" message, ventilating quickly or slowly according to the external conditions. For unfavorable external conditions, fast ventilation (3-5 minutes) was recommended to maintain internal comfort. Vice versa, for favorable conditions, it was asked to opt for more prolonged ventilation (15-20 minutes). Additionally, the increase of CO_2 level (to turn on the relative discomfort signal) was simulated by the observer with a solution of soda and vinegar.

Before the task, the tester was invited to imagine an ideal scenario and to indicate his/her strategy without reading the information on the display. The situation was illustrated in the following way:

> “*You are at the desk in this room, and the window and door are both closed. Suddenly, ‘inside air is bad’ turns on.* (During current wind conditions) *What would you do to ventilate this room efficiently?*”

The answers were compared with the choices made during the use of the prototype. Thus, it was possible to demonstrate the impact of the information provided by the system on user ventilation strategies.

‘Part 4’ concluded the case study by focusing on the aspects of learnability, usability, and satisfaction in the use of the system. At the end of the questionnaire, there was room for impressions on the learning experience and suggestions related to design in general.

Along with the survey, indoor and outdoor environmental data were collected. Specifically, T_{ind}, T_{out}, RH_{ind}, RH_{out}, $CO_{2\,ind}$, T_{globe}, and wind speed were monitored with the use of monitoring stations, anemometers, and the Data Logger already introduced in previous chapters. This time, as suggested by F Nicol (2012), the globe temperature was recorded to easily measure the mean radiant temperature (and operative temperature) for comfort assessment [20]. In addition to the monitored data, the serial data from both *Arduino* were also collected as text format. Thus, the recordings were compared with the messages read by the testers.

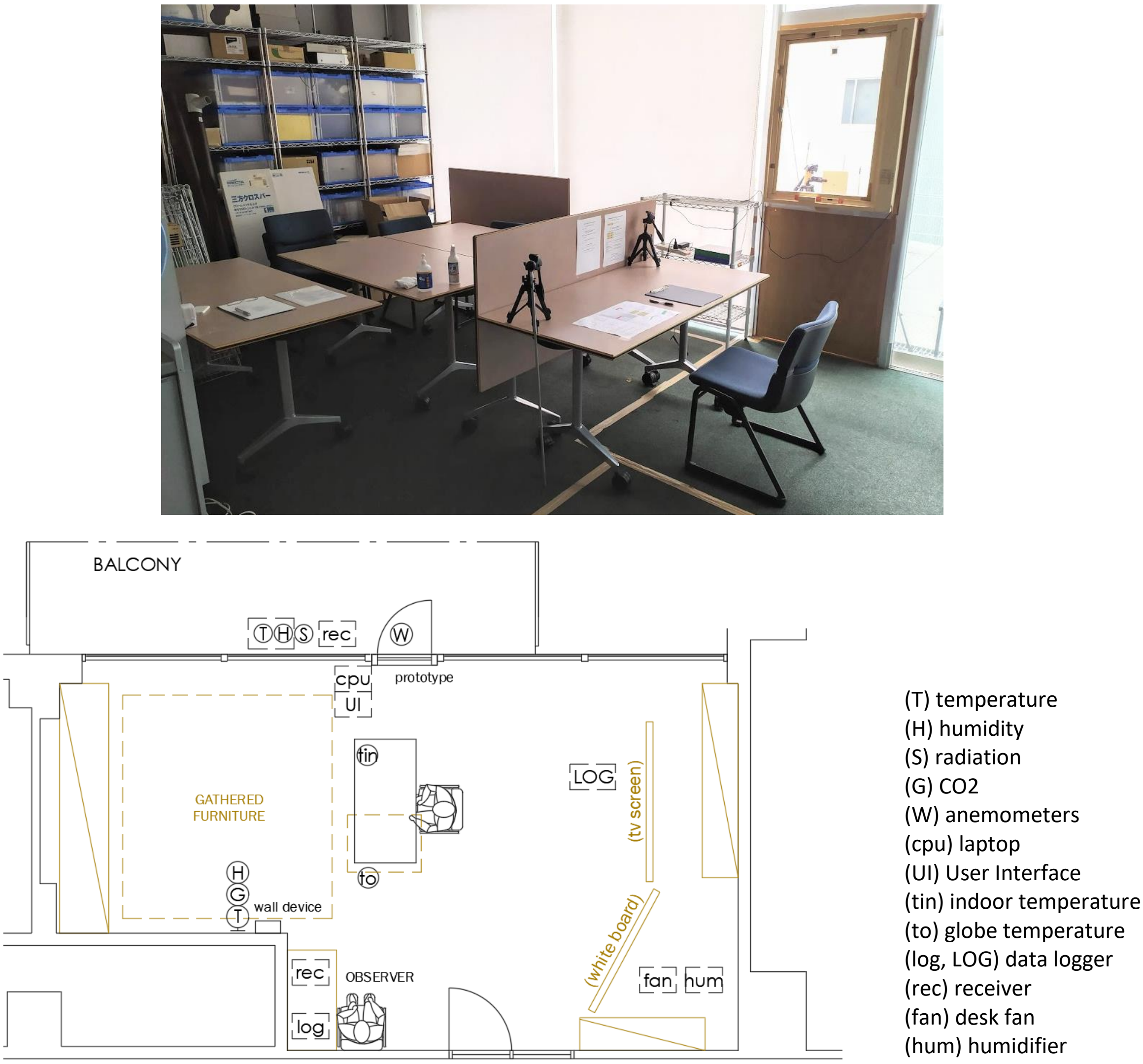

Figure 86. Image from the testing room configured for the 'Case Study II' (above), and the general layout of the experiment (below).

'Figure 86' (above) shows the layout of the room during the test. The indoor Monitoring Station RTR-576 was placed near the wall device to favor similar data recordings. Specifically, when the tester was not operating the window, he/she was seated at the table in the center of the room, in the axis between the window and the opposite door (see 'figure 86' (below)). Additionally, in two of the sessions, humidity levels were raised with a humidifier connected to a table fan hidden from the sight.

The analysis and discussion were based on before-after information comparison of data and organized into three levels. The table below synthesizes the analysis procedures, as discussed in the next subsection.

Table 33. Analysis and discussion procedure for 'Case Study II.'

Analysis Level	**Discussed data**
Level 1: General analysis - The survey in *Part 1* and *4* - Monitored data (indoor, outdoor conditions)	- Frequency of climate data and votes - Agree/disagree answers on the traditional use of window - Agree/disagree responses on usability, learnability, and satisfaction with the system
Level 2: Impact of the information displayed by the system - The survey in *Part 1* and *2* - Correlation of monitored data and votes - Serial data from the prototype	- Sensation votes and window messages regarding indoor conditions - Expectation votes and window messages regarding outdoor conditions - During-test agree/disagree answers on the initial use of the prototype
Level 3: The system as a tool to learn adequate ventilation times - Survey at the end of *Part 3* - Serial data from the prototype (opening angle and minutes to ventilate)	- The initial plan of the user and subsequent results of the action - Post-test agree/disagree answer about the task

4.6. The results of the experiment

The following text describes the results of the campaign. The discussion is based on the previous table, considering general aspects and more detailed comparison related to feelings and window information. Eventually, starting from the initial hypothesis and limits, the possible conclusion and following steps are indicated.

4.6.1. General data analysis and discussion

As already described, the method of data collection involved the recording of environmental data from the monitoring stations used for 'Case Study I' and other tests carried out previously (see 'Chapter II'). 'Table 34' describes the general data used for the following case study.

At the beginning of the analysis, it was discussed the general information about the subjects, the frequency of the climatic parameters, and the votes on the sensations and expectations towards external conditions. A total of 6 volunteers within the university participated in the test. Notably, *clo* levels were in line with the summer period (average *clo* = 0.84), and the testers were five males and one female, with an average age of around 40 years (between 32 and 65).

‘Figures 88, 89’ compare the frequency of climate data with the totality of the sensation votes. Thermal sensation votes had responses that range from -3 to 3, with 0 considered as neutral value. For details, see ‘table 35’.

Table 34. Description of the collected data for ‘Case Study II.’

Variable	*N*	*Minimum*	*Maximum*	*Mean*	*Std. Deviation*
Indoor operative temp °C	114	25,8	29,2	27,5	1,07
Indoor air temp °C	156	26,8	30,5	28,7	1,23
Indoor Relative Humidity %	156	46,0	81,0	63,5	11%
CO_2 Concentration (ppm)	156	570	1021	795,5	94
Outdoor air temp °C	116	24,4	31,1	27,8	1,90
Outdoor Relative Humidity %	116	41,0	81,0	61,0	8%
General answers	350	-	-	-	-
Thermal Sensation Votes	12	-1	2	0,5	1,00
RH Sensation Votes	12	0	2	1,0	0,80
AQ Sensation Votes	12	-2	0	-1,0	0,67
Thermal Expectation Votes	12	-1	2	0,5	0,80
RH Expectation Votes	12	0	2	1,0	0,52
Wind Velocity Expectation Votes	12	-2	1	-0,5	1,07
Actual Comfort Votes	12	-2	3	0,5	1,54
Clothing insulation (clo)	20	0,82	0,85	0,84	0,01
Total answers	454	-	-	-	-

Table 35. Range of answers selected for the study.

Kind of vote	**Range of answer**
Thermal	-3 (very cold) ÷ 3 (very hot); 0 is neutral
Humidity	-3 (very low) ÷ 3 (very high); 0 is ok
Air quality	-2 (very bad) ÷ 1 (very good); 0 is good
Wind	-2 (calm); -1 (gentle); 0 (breezy); 1 (strong)
Actual comfort	-3 (very bad) ÷ 3 (very good); 0 is neutral
Agree/disagree	-3 (totally disagree) ÷ 3 (totally agree); 0 is nor agree or disagree

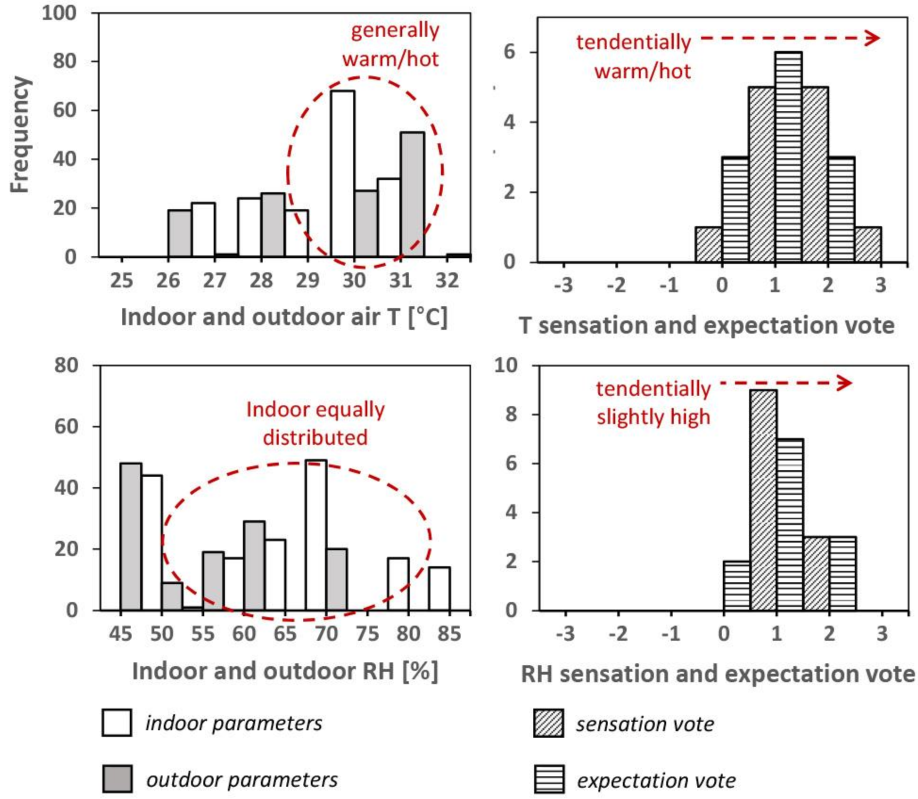

Figure 87. Air temperature and humidity data next to expectation and sensation votes.

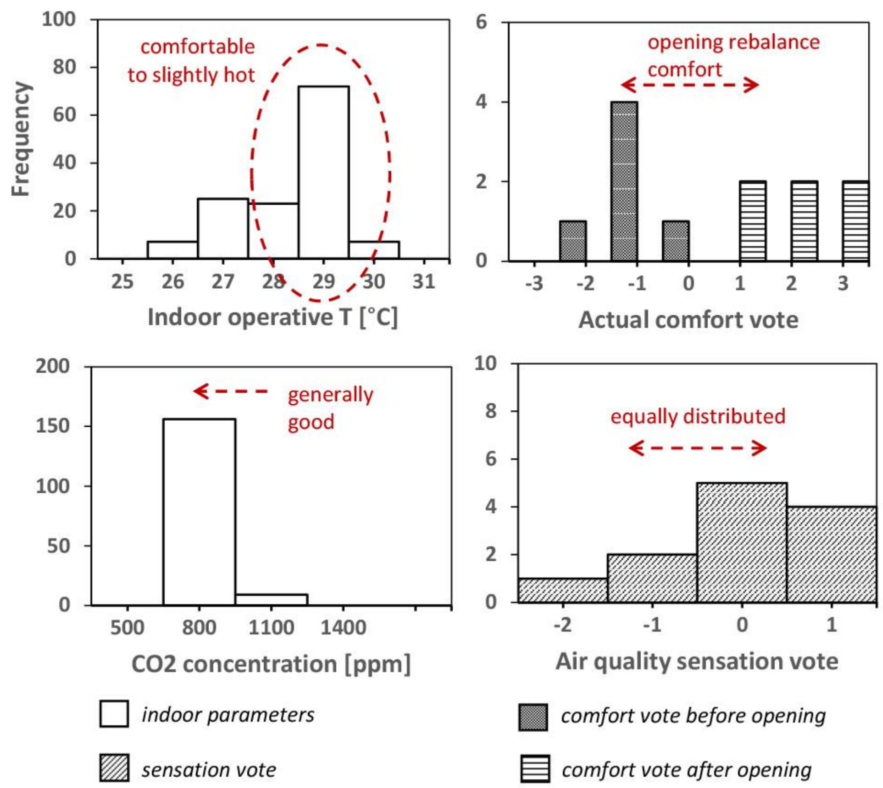

Figure 88. Operative temperature and CO_2 concentrations next to comfort and sensation votes.

The two charts in ‘figure 87’ (above) indicate that the temperatures were generally high during all the tests. This characteristic was reflected in the sensations experienced by the subjects. With the values from -3 (very cold) to 3 (very hot), the thermal sensations and expectations towards the outside were towards positive values (slightly hot and hot).

The indoor humidity was generally within the comfort values (see ‘figure 87’ below). However, on three occasions, it was modified before the sessions. As a result, the feeling and expectations towards the humidity followed the monitored data, being tendentially above the comfort values, between slightly high (+1) and high (+2).

‘Figure 88’ (above) illustrated the internal operative temperature alongside the actual comfort votes. The operating temperature was often at the limits between comfort and slightly hot, an aspect that was perceived by the testers. Additionally, the graph shows a general improvement in comfort thanks to natural ventilation at the time of opening the window.

As regards the air quality, the bar graphs show low CO_2 concentration. It was mainly due to the low use of the room by individuals and groups during the pandemic. However, the sensations votes showed an estimation of the quality tending to negative values (see ‘figure 88’ below).

The general data confirmed the results of ‘Case Study I.’ Even if the number of samples was not high, it was evident how testers had difficulty in perceiving the humidity and CO_2. Specifically, there was an apparent disagreement in predicting external humidity. For wind expectations, there were not enough frequency data to compare votes and parameters. However, as a reference, the data from the *Arduino* serial monitor, indicating the messages referred to the ventilation, were used.

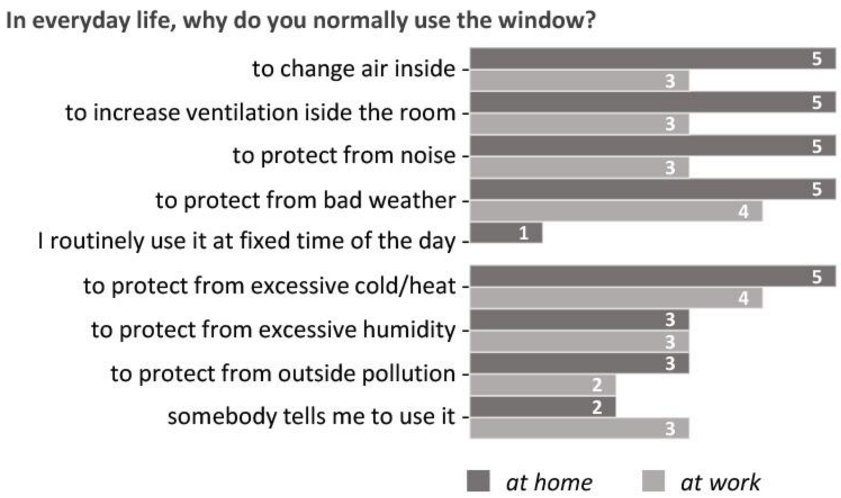

Figure 89. Answers referred to daily use of windows.

Regarding the direct questions, all participants thought that the window is a good way to achieve thermal comfort and air quality. Additionally, 'Figure 89' visualizes the first group of answers regarding the drivers that induce the testers to operate the window. As the results indicate, the most significant number of answers was for the exchange of air (especially at home), subsequently the management of temperature and ventilation. Unexpectedly, few said to use the window following a pre-established routine.

Subsequently, in 'figure 90', it is shown the second group of answers about the usual method of ventilation. The testers generally said to check the time before using the window and also use the opposite door to increase ventilation. Secondly, they affirmed to alternate the use of active devices with that of the window. Eventually, other aspects reflected more indecision. In specific, the discomfort was only partially considered at the base of their adaptive behavior.

Concluding, the first group of answers confirmed the observation made during the literature review on the factors triggering human-window interaction. In the meantime, the responses fit with the user profiles and the comfort scenario proposed in 'Chapter III.' Then, the second group suggested the usefulness of the system. Notably, the votes indicated how the LBVW could help to clarify external conditions and promote the use of the window on behalf of the active systems. Additionally, it could tell how and when to use the doors to increase ventilation.

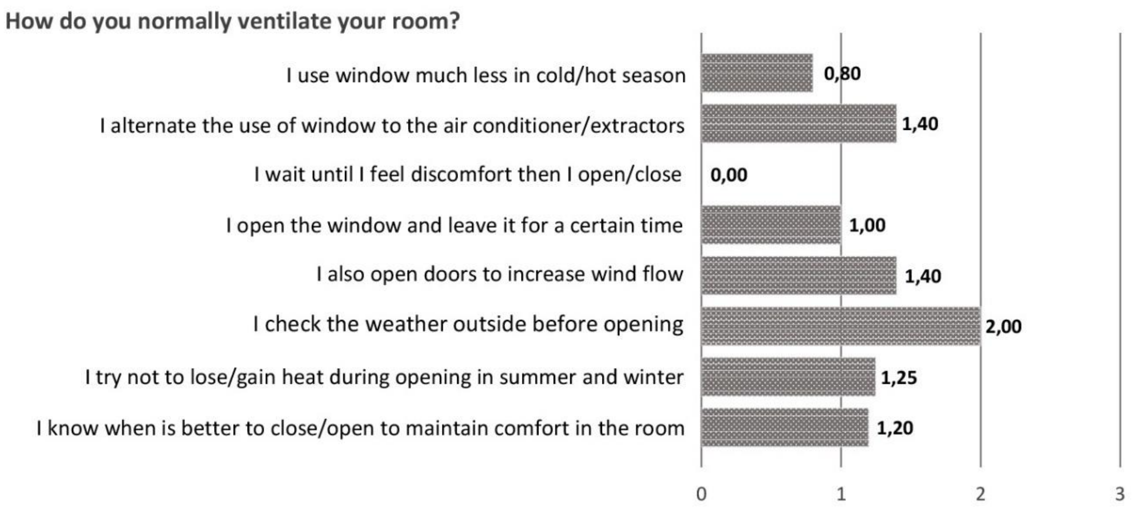

Figure 90. List of votes referred to ventilation habits.

4.6.2. Part 2 - Exploring the prototype for comfort

In this subsection, the sensation votes are correlated with the parameters indicated by the window to discuss the impact of information on learning internal and external environmental aspects and their effectiveness in describing the situation. Afterward, it is reported the opinion regarding the signals and the data displayed on the screen.

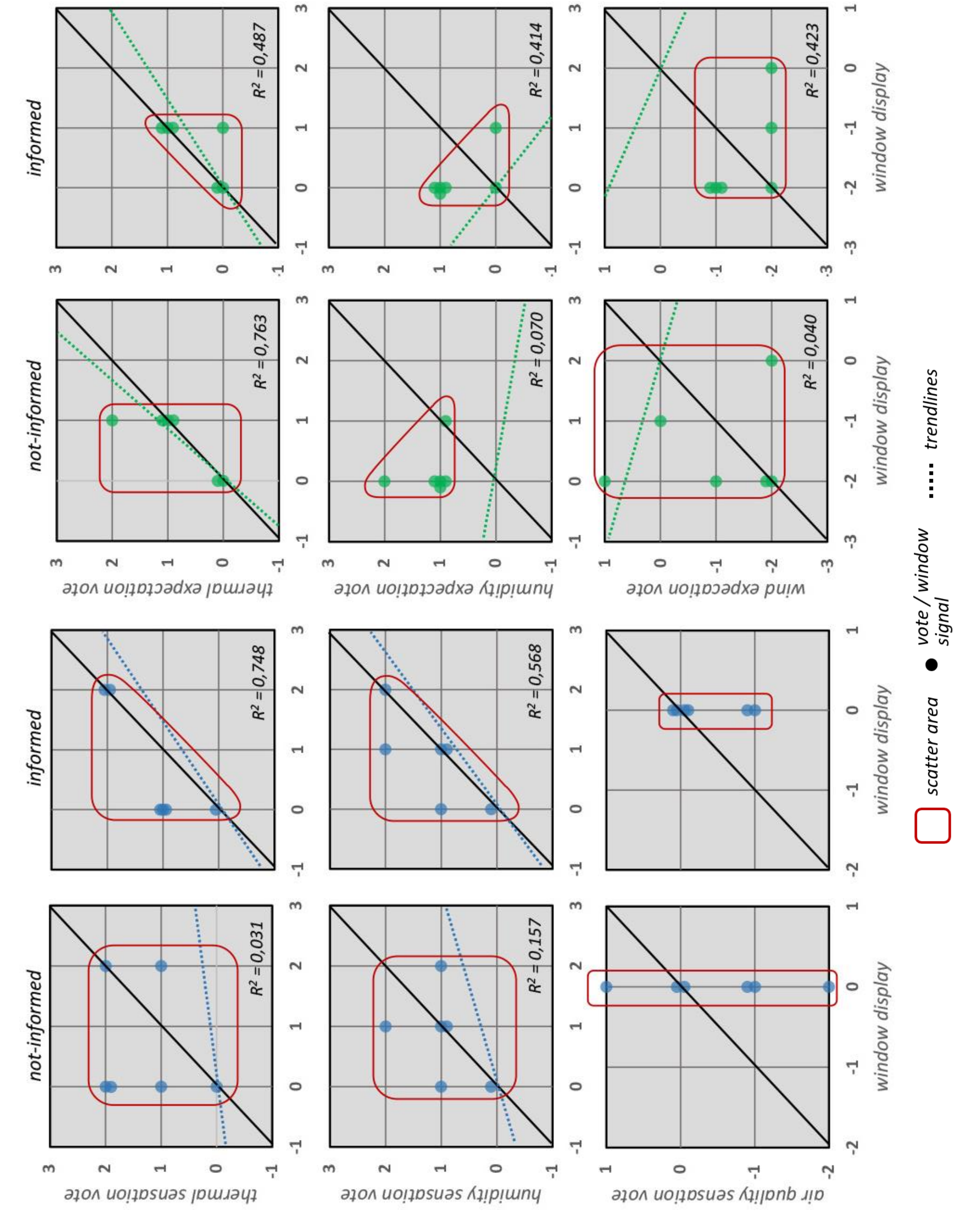

Figure 91. Correlations between the tester votes and information displayed by the window. The subplots indicate the correlation with sensations (blue dots) and expectations (green dots).

The scatter plots in ‘figure 91’ show the correlation between the information displayed, the sensation votes (blue dots), and the expectation votes (green dots) of each tester. Additionally, they are divided into not-informed (left column) and informed (right column) based on before/after reading the data in the display. During the test, it was stressed the importance of describing personal feelings about the indoor environment, regardless of the messages displayed by the window.

According to the results, there was a reduction in the scatter areas, often bringing the trendline closer to the 45° diagonal, which represented the equality between the displayed information and opinion. Firstly, by observing the sensation votes of temperature and CO_2, there was a marked variation in the responses. The exception was represented by the RH plot, where people remained more stable in their opinions. Secondly, the thermal expectation votes also indicated a trendline in proximity to the 45° diagonal and high R-squared values. Likewise, in the case of wind speed expectations, the scatter area reduced from left to right, which indicates that the testers agreed with the wind information. Conversely, other parameters gave negative trends or low correlations. Specifically, in RH expectations, there was no evident variation in the trends, but the increments in R-squared could denote that the subjects relied on the information of the system.

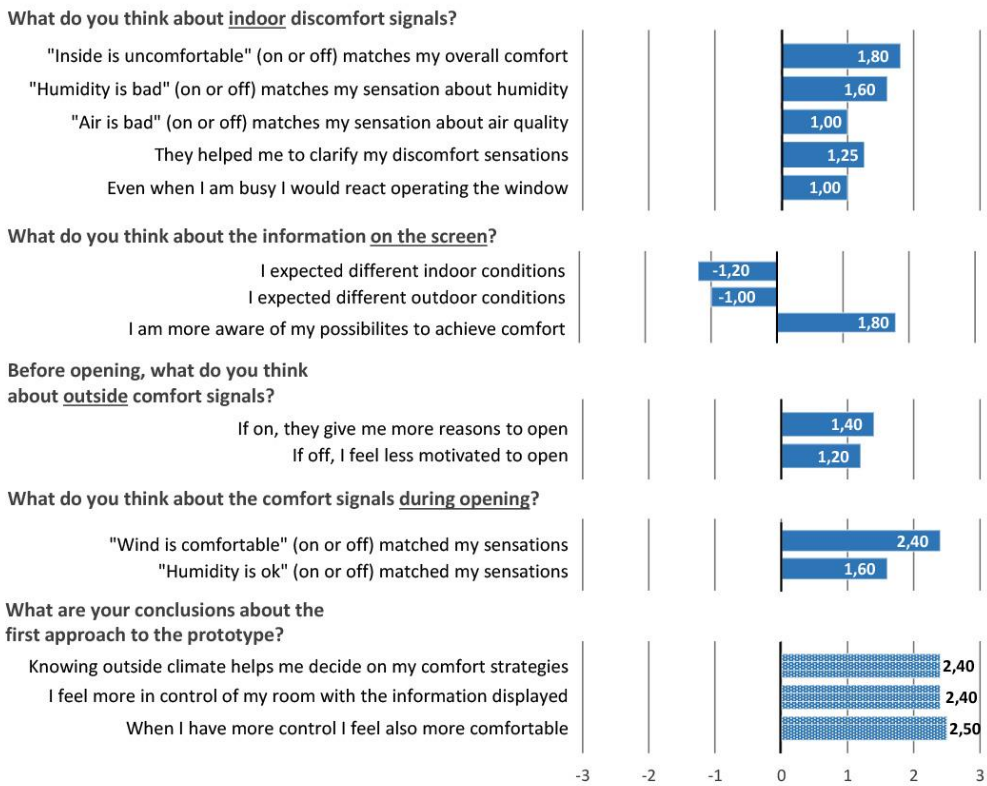

Figure 92. Testers’ answers referred to the first approach to the prototype.

Subsequently, the answers in ‘figure 92’ referred to the questionnaire on the effectiveness of the comfort/discomfort signals. The responses were generally positive, oscillating between slightly agree (+1) and agree (+2). Specifically, the discomfort signals were useful in describing the conditions of temperature and humidity. Likewise, the two comfort signals referring to wind conditions and humidity were considered positively. Additionally, about opening intentions, the subjects were generally invited to open when the signals were on, and less motivated when they were off.

By observing the detailed information on the display, the testers indicated that they did not expect different external or internal environmental conditions, which contrasted with the votes shown in ‘figure 92’. However, they considered the signals a way to strengthen the awareness of how to achieve comfort.

At the end of the survey, when asked "*what are your conclusions about the first approach to the prototype?*", the subjects sharply confirmed that knowledge of the climatic aspects helped to decide on comfort strategies. Furthermore, the provisional information increased the perception of control and, consequently, of comfort.

To conclude, the results of ‘Part 2’ tended to be in favor of the system. The window influenced a change of opinion regarding the conditions of the environment, which could be an indication of an initial learning process. The positive opinions regarding the effectiveness of the comfort/discomfort signals indicated the system capability in describing the environmental situation and in providing opportunities for its use.

4.6.3. Part 3 - Reaching adequate ventilation time

The third part focused on observing the resolution of the task related to adequate air exchange. As happened in the previous part, I compared the answers regarding the subject's intentions in resolving the ventilation, with the behavioral results that followed the information reading. For this purpose, starting from a window and door closed condition, it was considered "adequate" ventilation, the one that permitted to achieve the goal in the shortest possible time.

The graph of "figure 93" (on the next page) shows the starting plans of the testers to keep the door closed/open and how much to open the window (P value). Then, it is displayed how they solved the task (R value). The horizontal lines indicate the subjects who relied on their initial plan, while accentuated diagonals indicate a change of approach. In this sense, most of the testers adopted a different behavior after reading the information on the UI.

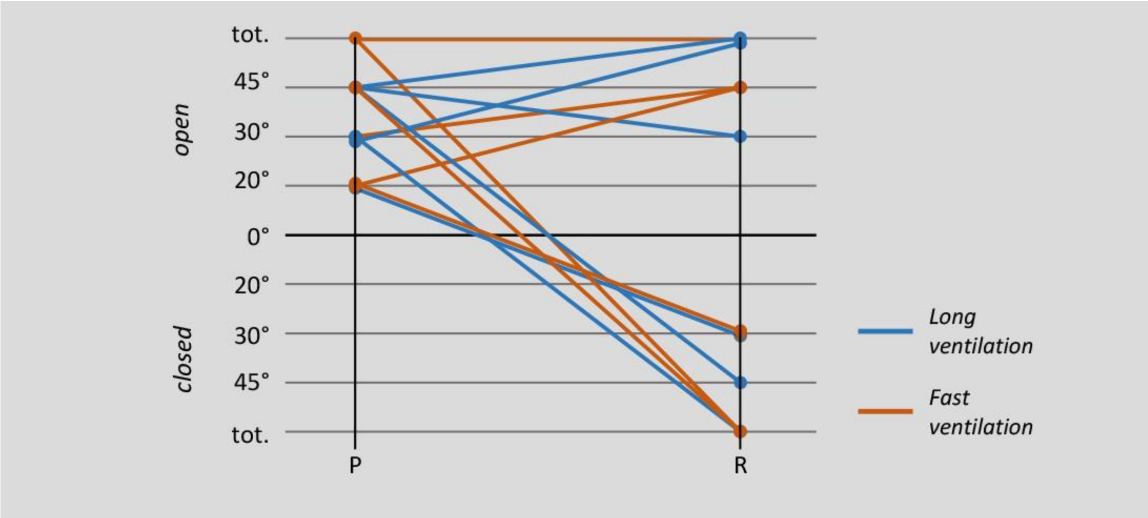

Figure 93. Users' change of plan after reading the information displayed by the system.

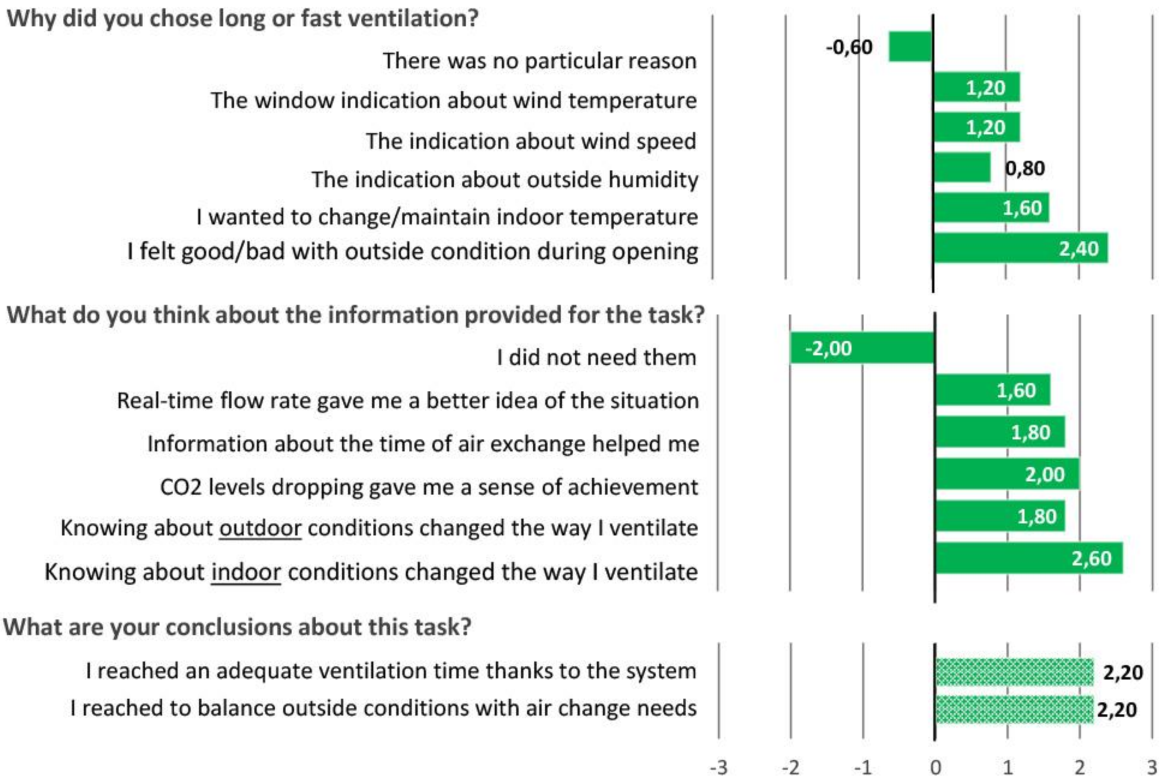

Figure 94. Testers' responses at the end of the ventilation task.

At the end of the task, the testers answered questions related to the experiment. As shown in 'figure 94', the reasons that guided the choice between long and fast ventilation are generally linked to the sensations experienced during the opening and to the will of maintaining or changing indoor conditions. In the second place, they indicated wind speed and temperature descriptions as useful indications. Furthermore, the information provided to resolve the task was helpful, especially the ‘minutes to clean’ the room. Additionally, reading CO_2 and flow rate data was considered a way to reinforce the impression of obtaining a concrete result.

At the end of the survey, answering the question "*what are your conclusions about this task?*", the testers indicated that the awareness of climatic conditions influenced their ventilation method (especially indoor conditions). Finally, the subjects considered that the system helped to solve the given task. Additionally, they believed that it could support balancing the aspects of comfort with the need for air exchange.

Concluding, the task proposed in ‘Part 3’ showed the possibility of the window to influence the approaches to air exchange. The graph that compares ventilation plans and results indicated potential initial learning in favor of the system, while the final question confirmed the general contribution of the window to ease the achievement of adequate ventilation as requested by the task.

4.6.4. Part 4 - Learnability and satisfaction using the system

The fourth and conclusive part of the test focused on the usability, learnability, and satisfaction aspects found during the approach to the system, which was organized into three distinct sets of answers. As in the previous parts, the answer score was measured based on the agreement/disagreement on a series of statements. ‘Figure 95’ (on the next page) shows that the responses were generally positive.

The first group of answers indicated that the system was generally useful. Among the responses, (‘figure 96’ above), the most significant reason was that it facilitated the achievement of comfort ("*it makes comfort tasks easier to get done*") and subsequently, to save energy (*"it can save energy when I need to ventilate* "). Eventually, about ventilation, there was a strong agreement regarding the prospects for energy savings. At the same time, the statement regarding efficiency ("*it saves me time when I need to ventilate*") was positive but less convincing.

The system also appeared to meet user expectations regarding the functions. One of the subjects analyzed the benefits linked to the management of air quality and the alternation with other devices:

> *“I think the system can effectively help me to improve air quality. Especially when it's too hot or too cold outdoor to open the window all day. (...) with the help of the window, I may avoid the use of an air conditioner, which I never really like to use! Also, for the post-corona conditions, it helps to improve health conditions, too!”*

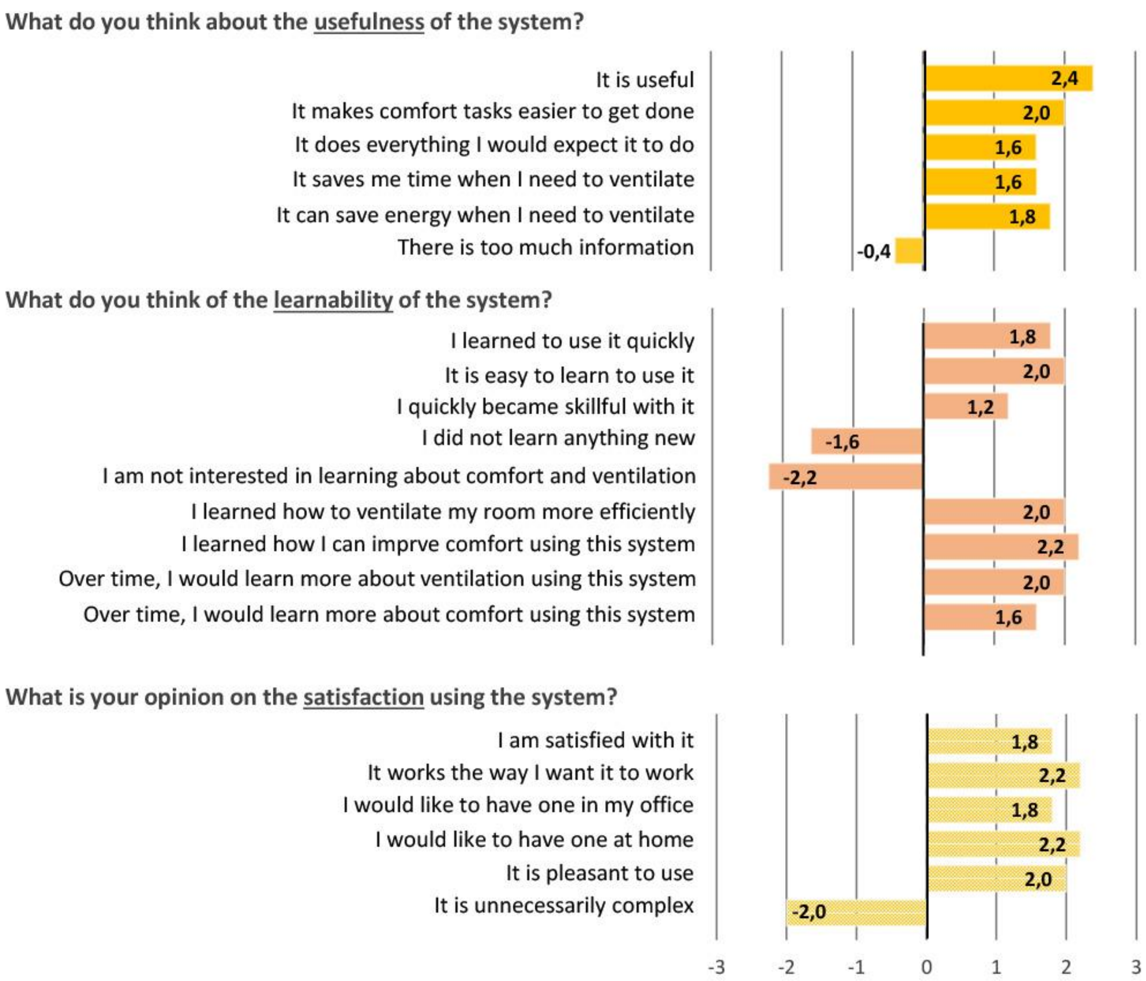

Figure 95. Testers' responses to the usefulness, learnability, and satisfaction of the system.

However, the answers also highlighted strong indecision on the amount of information during the window operation. Two of the subjects expressed difficulties in reading the detailed information provided by the prototype, while others referred to the average of the values. Below it is reported some of the testers' commentaries:

"(I suggest a) more clarity and a different location of the information on the prototype."
"Display speed is a little fast for me."
"Instead of instant values in the display, an average would be enough and easy to read."
"*I would like (the window) to compare outside/inside conditions before sending me the discomfort message.*"

All of them were mainly connected to technical issues that will be solved with future dedicated programming. The speed of "information scrolling" from the *Arduino*, had to match readability with the velocity of the window opening to produce a sensation of interactivity. In the final version of the user interface, there will be fixed parts and symbols to solve the matter. Additionally, the programming will produce a constant average of the values regarding climate conditions and possibly balance indoor discomforts with outside opportunities. However, instant information will be maintained for the opening angle to create a smooth visualization during hand movements.

The second group of questions, referring to learnability, also found favorable opinions (see ‘figure 96’, middle). In general, the score was high when it referred to learning about efficient ventilation and comfort management. Besides, the testers clearly said they were interested in understanding how to ventilate and that they learned something new. Notably, the highest score referred to the ease of access ("*It is easy to learn to use it*") and learning speed ("*I learned to use it quickly*"). On this matter, one of the testers stated that:

> *“It was easier to learn and use than I would imagine. The light system and messages on the display confirmed my body sensations.”*

Instead, the opinion on the ability to fully control the system ("*I quickly became skillful with it*") had a lower score.

Furthermore, the questions about the system's long-term learnability made the testers affirm that "*Over time, I would learn more about ventilation using this system.*". In the second place, the subjects were interested in learning about comfort issues. Eventually, some of them considered that the system was a useful learning tool. In particular, learnability was linked to air quality and ventilation. In the text below, there are some responses in this regard:

> “*This (system) indicates the potential that the provision of information facilitates learning with windows.”*
> *“It is effective for learning about air condition and ventilation, especially if you have one room and one door, which is common in Japan.”*
> *“The air quality is difficult to evaluate, and the window taught me how to behave. I would like to use it in daily life!”*

The satisfaction with the system was more linked to the way it could be used at home (see ‘figure 96’ (below)). The testers mainly declared that the system worked in line with their needs ("*it works the way I want it to work*"), and that was pleasant and simple to use (negative opinion to "*it is unnecessarily complex*"). Additionally, there was a higher preference for having the system at home than in the workplace. For instance, a tester considered:

> "*Being that I need time to know what to do, I feel I won't have it when I'm working. (...) It might be helpful to give me more clear commands.*"

At the end of the survey, people expressed various suggestions. Two comments were related to the potential of the system in the case it included automated systems. Notably, the testers suggest complete or partial automation:

> *"Sometimes, I don't want to walk to the window to open it because I'm very lazy. I want to trust the system most of the time, so it can open or close the window when needed by itself."*
> *"An automated system at night might be good. I cannot learn when I'm sleeping, and the window helps me to maintain air quality when I don't use it."*

Other opinions alluded to the content of the information, which was more related to the personality of the subjects. Some testers expressed the desire to receive information on the external sound level but also concerning external contaminants:

> "*Noise. I would like to know the decibels of sound coming from outside.*"
> "*I'm very concern about air pollen and sand from China, so I'd like to know that before I open.*"

Regarding the information, but this time commenting on the sending method, a subject suggested different signaling levels (sound and light) depending on the importance of the discomfort message. He/she stated that:

> *"I would like to receive an alarm only when air quality is bad because it is dangerous for my health. For the discomfort message, it can be just a light if it's not severely uncomfortable."*

In the end, there were indications regarding the system's ability to receive information from the subject, particularly regarding the condition and location:

“*It would be great if the window recognizes where I stand inside the room. Because I feel different when I’m near the window*.”
“*Feedback from my body, especially the temperature, so the window knows better when I feel comfortable or not.”*

As already discussed at the end of ‘Chapter III,’ both could be addressed via machine learning. The first aspect could be resolved using a high definition radar, already standard in some smartphone models. The window would not only be able to detect distance but also counting people and predict their intention depending on body movement. The second aspect could be implemented with the use of a thermal camera. It could be integrated into the inner sash of the system and dedicated to reporting skin temperatures of the subject. Having that information could improve the algorithm, balancing body metabolic rates with inside operational temperatures and external wind conditions.

4.6.5. Limits of the test

The general spread of the *Covid-19* pandemic drastically reduced the assembly of people and access to the campus facilities. Therefore, ‘Case Study II’ was strongly affected by the number of participants and the duration of the experiment.

First, the above limits were reflected in the number of samples collected (see ‘table 34’ for detailed information), and in ‘Part 2’, on the instability of R-squared values and in the trendlines reliability. There was also a little variation of climatic conditions, reducing the range of data only to some results.

Second, as mentioned during the discussion of the results, there were technical and coding limits given by the prototype. As a result, the information shown reflected only partially the idea of interface proposed in the previous chapters. Furthermore, the constraints on the connection between the wall device and the window made it necessary to separate some information and signals, confusing some testers.

4.6.6. Conclusions

Considering the limits discussed, the conclusion to the test could only give some indications and suggestions on how to proceed according to the results. The purpose of ‘Case Study II’ described in this section was to test the effectiveness of the prototype in triggering an initial learning process in favor of ventilation and awareness of one's environment.

First, the results indicate that the prototype could describe comfort and discomfort situations. Especially, it matched testers' sensation on indoor discomfort and humidity levels. Furthermore, it correctly described wind and its impact on comfort.

Second, indoor and outdoor data influenced the subjects’ opinions on feelings and expectations. In particular, most of the votes converged towards the system indications about CO_2 and temperature sensations and wind expectations.

Third, the data displayed by the prototype influenced how testers performed the ventilation task. In this case, real-time window angle, flow rate, and minutes to ventilate the room, sharply contributed to change initial ventilation strategies.

In conclusion, the test outcomes were considered a hint that confirms the initial hypothesis. In general, it could make people aware of discomfort conditions and suggest comfort opportunities given by the outdoor climate. Then, it could support ventilation tasks balancing IAQ and energy saving. Future improvement could be obtained by implementing machine learning mechanisms to permit the LBVW system to adapt to different users and situations.

The results of the conclusive case study favor future tests with the prototype aimed at providing more data on long-term processes, and on other learning methods that the LBVW system could potentially offer.

CHAPTER V
CONCLUSION AND PERSPECTIVES ON LBD SYSTEMS

CHAPTER V - CONCLUSION AND PERSPECTIVE OF LBD SYSTEMS

5.1. Summary of the aims and main results

At the beginning of this work, a list of aims was proposed. This section intends to clarify the main results based on those intentions and to assume future perspectives for this research. The thesis objectives and results can be summarized according to the points below:

- Discussing how feedback technologies can increase awareness about indoor comfort.

  The author tested people's capability to perceive the environment and analyzed feedback tools in the literature to indicate how to support comfort.
- Discussing traditional interaction with windows and learning opportunities.

  The author \reviewed the literature on drivers in human-window interaction and the role of control and knowledge.
- Identifying feedback parameters and modalities that can support people towards their comfort goals.

  The author illustrated a framework based on the LBD process indicating timing, message, and display techniques to support comfort and ventilation.
- Demonstrating how a window system based on feedback technologies can inform a Learning-By-Doing process on natural ventilation.

  The author devised a window system and described three comfort scenarios on how people can learn from it. Then, he constructed a 1:1 scale working prototype as a base to show an initial learning process.

The natural step forward of this work is to test the system for a more extended period and with a higher number of people during normal daily activities. At that time, it will be possible to describe with more certainty that the system is capable of supporting learning on comfort and ventilation in the long-term. For the scope, the LBVW will be further refined with more flexible programming, and the design improved also based on the suggestions received in the conclusive case study.

5.2. Conclusion and perspectives on LBD Systems

In this thesis, it was discussed the importance of involving inhabitants in the practices of comfort and energy management in the built environment. Windows occupy an essential part in the exchanging of external/internal heat flows and are a fulcrum that can improve air quality, indoor comfort while reducing energy consumption. Therefore, it was proposed how users could be supported through feedback technologies when using window systems in the search for comfort. Doing so, it was prefigured a situation that balances the qualities of automation with the ability of people to manage information in the most convenient place and time for their wellbeing.

The analysis of the feedback methods applied in other products suggested how designers can support or alter people's behavior with information. After illustrating different technological solutions, those feedback techniques were extended to the built environment, where communication is guided by the need for comfort and by the variability of the climate. Then, the logic of Learning-By-Doing was combined with the adaptive comfort approach, which adopts similar mechanisms.

The LBVW system ideated by the author represents an example of how long-term learning processes can be applied in building systems adopting embedded technologies. From a broader perspective, LBD systems might be able to provide learning processes that favor comfort and energy-saving involving the entire society in daily life practices based on more sustainable habits.

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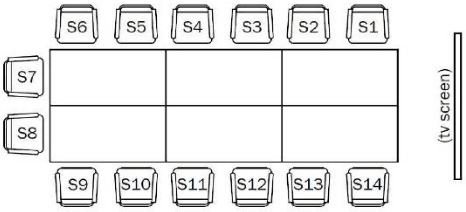
Annex A — Reference questionnaire for Case Study I

Thermal comfort survey
Today's date: Tuesday, 26 November, 2019

PRELIMINARY QUESTIONS - Mark the following answers with an "X"

POSITION
Mark your current seat with an "X"



Please write your age: ......
Please mark your gender: F M

CLOTHING (multiple choices)
a1) Which best describe your clothing now?

Short sleeve shirt/blouse	
Long sleeve shirt/blouse	
Vest	
Trousers/long skirt	
Shorts/short skirt	
Dress	
Pullover	
Jacket	
Long socks	
Short socks	
Tighs	
Tie	
Boots	
Shoes	
Sandals	
Other (specify)...	

GENERAL QUESTIONS - Mark the following answers with an "X"

FEELINGS

b1) How do you feel at this moment?	time 13:15	14:00	15:00
Very cold			
Cold			
Slightly cold			
Neutral (neither cold not hot)			
Slightly hot			
Hot			
Very hot			

PREFERENCE

b2) I would prefer to be:	time 13:15	14:00	15:00
Much cooler			
A bit cooler			
No change			
A bit warmer			
Much warmer			

FEELINGS

c1) How do you find the humidity?	time 13:15	14:00	15:00
Very humid			
Humid			
Slightly humid			
Neither humid nor dry			
Slightly dry			
Dry			
Very dry			

PREFERENCE

c2) I would prefer to be:	time 13:15	14:00	15:00
Much drier			
A bit drier			
No change			
A bit more humid			
Much humid			

FEELINGS

e1) How do you find air quality?	time 13:15	14:00	15:00
Very bad			
Bad			
Slightly bad			
Neither bad nor good			
Slightly good			
Good			
Excellent			

p1/2

FEELINGS (possible multiple choices)	time		
f1) Do you feel body temperature difference?	**13:15**	**14:00**	**15:00**
Cold lower legs/feet			
Cold hands			
Cold back/neck			
Cold face/head			
No temperature difference			
Hot lower legs/feet			
Hot hands			
Hot back/neck			
Hot face/head			

PREFERENCE	time		
f2) I would prefer to be:	**13:15**	**14:00**	**15:00**
Much cooler			
A bit cooler			
No change			
A bit warmer			
Much warmer			

GENERAL COMFORT	time		
g1) How would you rate your overall comfort?	**13:15**	**14:00**	**15:00**
Very comfortable			
Moderately comfortable			
Slightly comfortable			
Slightly uncomfortable			
Moderately uncomfortable			
Very uncomfortable			

p2/2

Annex B — Reference questionnaire for Case Study II

Evaluating the window system as a learning tool
Today's date:

Please mark your gender: F | M
Please mark your dresscode: (multiple choices)

Short sleeve shirt/blouse	☐	Long socks	☐
Long sleeve shirt/blouse	☐	Tie	☐
Trousers/long skirt	☐	Shoes	☐
Shorts/short skirt	☐	Sandals	☐
Short socks	☐		

PART 1 - PRELIMINARY QUESTIONS (Mark the following answers with an "X" , fill NA if not applicable)

	Y	N	Undecided
a) Do you think the window is a good way to achieve thermal comfort?	☐	☐	☐
b) Do you think the window is a good systems to achieve indoor air quality?	☐	☐	☐

c) In everyday life, why do you normally use the window? (multiple choices)

	At home	At work	Never
To change air inside	☐	☐	☐
To increase ventilation inside the room	☐	☐	☐
To protect from noise	☐	☐	☐
To protect from bad weather	☐	☐	☐
I routinely open/close it at fixed time of the day	☐	☐	☐
To protect from excessive cold/heat	☐	☐	☐
To protect from excessive humidity	☐	☐	☐
To protect from outside pollution	☐	☐	☐
Somebody tells me to use it	☐	☐	☐
Other factors (please fill below)			

....

....

d) How do you normally ventilate your room? (multiple choices)

	(totally disagree) -3	-2	-1	0	1	2	3 (totally agree)	(NA)
I use window much less in cold/hot seasons	☐	☐	☐	☐	☐	☐	☐	☐
I alternate the use of window to the air conditioner/extractors	☐	☐	☐	☐	☐	☐	☐	☐
I wait until I feel discomfort than I open/close	☐	☐	☐	☐	☐	☐	☐	☐
I open the window and leave it for a certain time	☐	☐	☐	☐	☐	☐	☐	☐
I also open doors to increase wind flow	☐	☐	☐	☐	☐	☐	☐	☐
I check climate outside before opening	☐	☐	☐	☐	☐	☐	☐	☐
I try not to lose / gain heat during opening in summer and winter	☐	☐	☐	☐	☐	☐	☐	☐
I know when is better to close/open to maintain comfort in the room	☐	☐	☐	☐	☐	☐	☐	☐
Other aspects (please fill below)								

....

....

e) What are your feelings about the indoor environment right now?

		-3	-2	-1	0	1	2	3	
How do you find the temperature?	*(very cold)*	☐	☐	☐	☐	☐	☐	☐	*(very hot)*
How do you find the humidity?	*(very low)*	☐	☐	☐	☐	☐	☐	☐	*(very high)*
How do you find air quality (CO2 level, 0 is good)?	*(very bad)*		☐	☐	☐	☐			*(very good)*

		-3	-2	-1	0	1	2	3	
f) How would you rate your overall comfort (0 is comfortable)?	*(very uncomfortable)*	☐	☐	☐	☐	☐	☐	☐	*(very comfortable)*
g) Can you understand how is the climate outside?									
How do you think the wind speed hitting the window is (0 is breezy)?	*(calm)*		☐	☐	☐	☐			*(strong)*
How do you think wind temperature is (0 is pleasant)?	*(very cold)*	☐	☐	☐	☐	☐	☐	☐	*(very hot)*
How do you think humidity is (0 is OK)?	*(very low)*	☐	☐	☐	☐	☐	☐	☐	*(very high)*

PART 2 - EXPLORING THE PROTOTYPE FOR COMFORT (Mark the following answers with an "X" , fill NA if not applicable)

[Wait for discomfort signals]

a) What do you think about indoor discomfort signals?

	(totally disagree)	-3	-2	-1	0	1	2	3	(totally agree)	(NA)
"Inside is uncomfortable" (on or off) matches my overall comfort										
"Humidity is bad" (on or off) matches my sensation about humidity										
"Air is bad" (on or off) matches my sensation about air quality										
They help me to clarify my discomfort sensations										
Even when I am busy I would react operating the window										

[Step near the window]

b) Before opening, what do you think about outside comfort signals?

	(totally disagree)	-3	-2	-1	0	1	2	3	(totally agree)	(NA)
If on they give me more reasons to open										
If off I feel less motivated to open										

Other opinions (please fill below)

....

[Read the information on the display]

c) What do you think about the information on the screen?

	(totally disagree)	-3	-2	-1	0	1	2	3	(totally agree)	(NA)
I expected different indoor conditions										
I expected different outdoor conditions										
I am more aware of my possibilities to achieve comfort										

d) After knowing the information, how do you feel about your room?

		-3	-2	-1	0	1	2	3	
How do you find the temperature (0 is comfortable)?	(very cold)								(very hot)
How do you find the humidity (0 is OK)?	(very low)								(very high)
How do you find air quality (CO2 level, 0 is good)?	(very bad)								(very good)

e) Can you report again how is the climate outside according to you?

How do you think the wind speed hitting the window is (0 is breezy)?	(calm)								(strong)
How do you think wind temperature is (0 is pleasant)?	(very cold)								(very hot)
How do you think humidity is (0 is OK)?	(very low)								(very high)

[Use the window freely then answer the remaining questions]

f) What did you think about comfort signals during the opening?

	(totally disagree)	-3	-2	-1	0	1	2	3	(totally agree)	(NA)
"Wind is comfortable" (on or off) matched my sensations										
"Humidity is OK" (on or off) matched my sensations										

		-3	-2	-1	0	1	2	3	
g) How is your overall comfort right now (0 is comfortable)?	(very uncomfortable)								(very comfortable)

h) Did you find any issues or curiosities using the window?

....

i) What are your conclusions about the first approach to the prototype?

	(totally disagree)	-3	-2	-1	0	1	2	3	(totally agree)	(NA)
Knowing outside climate helps me decide on my comfort strategy										
I feel more in control of my room with the information displayed										
When I have more control I feel also more comfortable										

Others (please fill below)

....

PART 3 -PRE-TASK - IMAGINE A POSSIBLE SCENARIO

You are at the desk in this room and both window and door are closed. Suddenly, "Inside air is bad" turns on.
What would you do to efficiently ventilate this room ...

a) ... fast (around 3-5 minutes) during the current external wind conditions?

I would keep the opposite door .... closed ☐ open ☐

Then, I would open the window .... 20° (tilted) ☐ 30° ☐ 45° ☐ totally open ☐

b) ... for a long time (around 15-20 minutes) during the current external wind condition?

I would keep the opposite door .... closed ☐ open ☐

Then, I would open the window .... 20° (tilted) ☐ 30° ☐ 45° ☐ totally open ☐

PART 3 - TASK: REACHING AN ADEQUATE VENTILATION TIME (Mark the following answers with an "X" , fill NA if not applicable)

[Please complete the task and answer the questions]

a) Which kind of ventilation did you decide to achieve? (multiple choices)

Fast ventilation (3-5 minutes) .... ☐

Long ventilation (15-20 minutes) .... ☐

b) Why did you chose long or fast ventilation?

	(totally disagree) -3	-2	-1	0	1	2	3 *(totally agree)*	*(NA)*
There was no particular reason								
The window indication about wind temperature								
The indication about wind speed								
The indication about outside humidity								
I wanted to change/maintain indoor temperature								
I felt good/bad with outside condition during opening								

c) What do you think about the information provided for the task?

	(totally disagree) -3	-2	-1	0	1	2	3 *(totally agree)*	*(NA)*
I did not need them								
Real time flow rate gave me a better idea of the situation								
Information about the time of air exchange helped me								
Co2 levels dropping could give me a sense of achievement								
Knowing about <u>outside</u> conditions changed the way I ventilate								
Knowing about <u>indoor</u> conditions changed the way I ventilate								

d) For the ventilation, was it necessary to open the opposite door? Y ☐ N ☐

e) At what angle could you achieve the ventilation? 20° (tilted) ☐ 30° ☐ 45° ☐ totally open ☐

f) What are your conclusion about this task?

	(totally disagree) -3	-2	-1	0	1	2	3 *(totally agree)*	*(NA)*
I reached an adequate ventilation time thanks to the system								
I reached to balance outside conditions with air change needs								

Others (please fill below)

....

(do not fill here)

Y ☐ N ☐ F ☐ L ☐

20° (tilted) ☐ 30° ☐ 45° ☐ totally open ☐

CONCLUSION - LARNABILITY AND SATISFACTION USING THE SYSTEM (Mark the following answers with an "X" , fill NA if not applicable)

a) What do you think about the usefulness/usability of the system?

	(totally disagree) -3	-2	-1	0	1	2	3 (totally agree)	(NA)
It is useful								
It makes comfort tasks easier to get done								
It does everything I would expect it to do								
It saves me time when I need to ventilate								
It can save energy when I need to ventilate								
There is too much information								

b) To make it more useful, would you like to know other information from distance or in the display?

....

c) What do you think of the learnability of the system?

	(totally disagree) -3	-2	-1	0	1	2	3 (totally agree)	(NA)
I learned to use it quickly								
It is easy to learn to use it								
I quickly became skillful with it								
I did not learn anything new								
I am not interested in learning about comfort and ventilation								
I learned how to ventilate my room more efficiently								
I learned how I can improve comfort using this system								
Over time, I would learn more about ventilation using this system								
Over time, I would learn more about comfort using this system								

d) Are there any other opinions or suggestions on the learning experience with the system?

....

....

e) What is your opinion on the satisfaction using the system?

	(totally disagree) -3	-2	-1	0	1	2	3 (totally agree)	(NA)
I am satisfied with it								
It works the way I want it to work								
I would like to have one in my office								
I would like to have one at home								
It is pleasant to use								
It is unnecessarily complex								

f) What is your conclusive impression about the system? There is something you would like to change about it?

....

....

....

....

Annex C − Programming code of the monitoring stations

This Annex contains the programming code of the LBVW prototype. There is the coding of the main window and the wall device. As previously indicated, control ranges were added to the normal monitoring readings. With this method, it was possible to use the PCBs both as a monitoring station and a control center.

```
MONITORING STATION (MAIN WINDOW) ////////////////////////////////////////////////////
// INCLUDING LIBRARIES ------------------------------------------------------------------------------------------------
#include <Adafruit_I2CDevice.h> //Thermocouple
#include <Adafruit_I2CRegister.h> //Thermocouple
#include "ClosedCube_HDC1080.h" // RH sensor
ClosedCube_HDC1080 hdc1080; // RH sensor
#include <SharpIR.h> //Proximity sensor
#include <SFE_BMP180.h> // Barometric Pressure Sensor
SFE_BMP180 bmp180; //Barometric Pressure Sensor name
#include "Adafruit_MCP9600.h" //Thermocouple
Adafruit_MCP9600 mcp; //Thermocouple
#include <sdpsensor.h> //Differential Pressure Sensor
SDP8XXSensor sdp1; //Differential Pressure Sensor 1 name
SDP8XXSensor sdp2; //Differential Pressure Sensor 2 name

// DEFINING THE MULTIPLEXER ADDRESS ------------------------------------------------------------------------
 #define TCAADDR 0x70
 void tcaselect(uint8_t i) {
 if (i > 7) return; //Addresses from 0 to 7 are now callable
 Wire.beginTransmission(TCAADDR);
 Wire.write(1 << i);
 Wire.endTransmission();
 }

//PINS AND VARIABLES FOR ANALOGUE SENSORS ---------------------------------------------------------------
 #define IR1 A9 //Indicating PIN for proximity sensor 1 (user)
 #define IR2 A10 //Indicating PIN for proximity sensor 2 (window)
 #define model1 1080 //GP2Y0A21Y PROXIMITY (model names according to the datasheets)
 #define model2 1080 //GP2Y0A21Y PROXIMITY
 SharpIR SharpIR1(IR1, model1); //Definition of variables for proximity sensor 1 (user)
 SharpIR SharpIR2(IR2, model2); // ... and proximity sensor 2 (user)

void setup() {
 Serial.begin(9600); // Starts the serial communication
 Wire.begin();
 delay(1000); // let serial console settle

// SETTING UP LEDS FOR COMFORT/DISCOMFORT SIGNALS --------------------------------------------------
 pinMode (8, OUTPUT); // White led
 pinMode (2, OUTPUT); // Red led
 pinMode (3, OUTPUT); // Green led
```

```
  pinMode (9, OUTPUT); //Green led
  pinMode (10, OUTPUT); //Green led

// SETTING UP RH SENSOR ------------------------------------------------------------------------------------------
  Serial.println("ClosedCube HDC1080 Arduino Test");
  tcaselect(1); //Indicating the Multiplexer position 1
  hdc1080.begin(0x40); //Initialize the sensor

// SETTING UP BAROMETRIC PRESSURE ----------------------------------------------------------------------------
  tcaselect(0); //Indicate the Multiplexer position 0
  bool success = bmp180.begin(); //Initialize the sensor

  if (success) {
    Serial.println("BMP180 init success");
  }

// SETTING UP THERMOCOUPLES ------------------------------------------------------------------------------------
  tcaselect(2); //Indicating the Multiplexer position 2
  tcaselect(4); //... and position 4
  tcaselect(5); //... and position 5
  while (!Serial) {
      delay(10);
    }
    Serial.println("MCP9600 HW test");

  /* Initialise the sensor without I2C ADDRESS. */
    if (! mcp.begin()) {
        Serial.println("Sensor not found. Check wiring!");
        while (1);
    }

  Serial.println("Found MCP9600!");

  /* Define type and resolution of the thermocouple */
  mcp.setADCresolution(MCP9600_ADCRESOLUTION_18);
  Serial.print("ADC resolution set to ");
  switch (mcp.getADCresolution()) {
    case MCP9600_ADCRESOLUTION_18:   Serial.print("18"); break;
    case MCP9600_ADCRESOLUTION_16:   Serial.print("16"); break;
    case MCP9600_ADCRESOLUTION_14:   Serial.print("14"); break;
    case MCP9600_ADCRESOLUTION_12:   Serial.print("12"); break;
  }
  Serial.println(" bits");

  mcp.setThermocoupleType(MCP9600_TYPE_T);
  Serial.print("Thermocouple type set to ");
  switch (mcp.getThermocoupleType()) {
    case MCP9600_TYPE_T:  Serial.print("T"); break;
  }
  Serial.println(" type");
```

```
  mcp.setFilterCoefficient(3);
  Serial.print("Filter coefficient value set to: ");
  Serial.println(mcp.getFilterCoefficient());

  mcp.enable(true);

// SETTING UP DIFFERENTIAL PRESSURE ---------------------------------------------------------------------------
tcaselect(3);//Indicating the Multiplexer position 3
tcaselect(6);//... and position 6

  do {
    int ret1 = sdp1.init();
    int ret2 = sdp2.init();
    if (ret1 == 0 && ret2 == 0) {
      Serial.print("initsdp(): success\n");
      break;
    } else {
      Serial.println("initsdp(): failed");
      Serial.print ("ret1:");
      Serial.println(ret1);
      Serial.print ("ret2:");
      Serial.println(ret2);
    }
  } while(true);
}


void loop() {

// LOOP RH SENSOR ---------------------------------------------------------------------------------------------------
  tcaselect(1); //Indicating the Multiplexer position 1
  float rhout = hdc1080.readHumidity()-6; //Indicating variable and correction (-6)

// LOOP PROXIMITY SENSOR -------------------------------------------------------------------------------------------
  unsigned long bounce1=millis(); //Taking time before the readings

  int dis1=SharpIR1.distance(); //Primary variable for user presence
  int dis2=SharpIR2.distance(); //Primary variable for window distance

// LOOP BAROMETRIC PRESSURE SENSOR -----------------------------------------------------------------------------
  tcaselect(0); //Indicating the Multiplexer position 0

  char status;
  double T, P; //Indicating variables (temperature, pressure)
  bool success = false;

  status = bmp180.startTemperature();

  if (status != 0) {
    delay(1000);
    status = bmp180.getTemperature(T);
```

```
  if (status != 0) {
    status = bmp180.startPressure(3);

    if (status != 0) {
      delay(status);
      status = bmp180.getPressure(P, T);
      }
    }
  }

// LOOP ANGLE AND AREA ----------------------------------------------------------------------------------------------
 float tn = (float)dis2 / (float)37; //Declaring tangent tn
 int ang = atan(tn)*180/3.14; //Primary variable of the window angle
 float i= 1.2152*sin(radians(ang/2))+0.3844*sin(radians(ang)); //i for the next formula
 float Aeff = sqrt(1/(2.708722+1/pow(i,2))); //Secondary variable of the window area

// LOOP THERMOCOUPLE GLASS ---------------------------------------------------------------------------------------
 tcaselect(2); //Indicating the Multiplexer position 2
 float Tglass = mcp.readThermocouple(); //Primary variable for glass temp.

// LOOP THERMOCOUPLE AIR -------------------------------------------------------------------------------------------
 tcaselect(4); //Indicating the Multiplexer position 4
 float Tout = mcp.readThermocouple(); //Primary variable for outside temp.

// LOOP THERMOCOUPLE IND ------------------------------------------------------------------------------------------
 tcaselect(5); //Indicating the Multiplexer position 5
 float Tind = mcp.readThermocouple(); //Primary variable for indoor temp.

// LOOP DIFFERENTIAL PRESSURE AND FLOW RATE ------------------------------------------------------------
 tcaselect(3); //Indicating the Multiplexer position 3
 //defining all the variables for the formulas
 int ret1 = sdp1.readSample();
 float pre1 = sdp1.getDifferentialPressure();
 float x1 = (pre1*2/1.225); //Input differential pressure and air density
 float vel1 = sqrt(abs(x1)); //Secondary variable of the wind speed entering the window
 float Q = 0.65*Aeff*vel1; //Flow rate window partially open
 float Qt = 0.65*0.576*vel1; //Flow rate window totally open
 float ACR = Q/88.5; //Air change rate with window partially open
 float ACRt = Qt/88.5; //Air change rate with window totally open
 int minleft = 1/ACR/60; //Minutes to clean with window partially open
 int minleftt = 1/ACRt/60; //Minutes to clean with window totally open

 tcaselect(6); //Indicating the Multiplexer position 6
 int ret2 = sdp2.readSample();
 float preb = sdp2.getDifferentialPressure(); //Differential pressure and air density
 float x2 = (preb*2/1.225);
 float vel2 = sqrt(abs(x2)); //Secondary variable of the wind speed outside the window
 float windcond; //Variable to separate measurement depending on window angle

// LOOP INDOOR COMFORT ---------------------------------------------------------------------------------------------
```

```
  float Tr = (Tind + Tind + Tglass)/3;
  float Topls; //Superior limit of the operative temperature
  float Topli; //Inferior limit of the operative temperature
  float Top; //Secondary variable of the operative temperature
  float Tom = 22.84; //ref to June

  if (ang > 18 && vel1 > 0.6) { //Inserting comfort formula form ASHRAE 55
   Top = (0.7*Tind + (1 - 0.7)*Tr);
   Topls= (0.31*Tom)+21.3+1.8;
   Topli= (0.31*Tom)+14.3-1.8;
  }else if (ang > 18 && vel1 < 0.6){
   Top = (0.4*Tind + (1 - 0.4)*Tr);
   Topls= (0.31*Tom)+21.3;
   Topli= (0.31*Tom)+14.3;
  }else{
   Top = Tr;
   Topls= (0.31*Tom)+21.3;
   Topli= (0.31*Tom)+14.3;
  }

//INFO LINE 1: CENTRAL SECTION ------------------------------------------------------------------------------------
 /* The next code refers to the central section of the interface (WFB2) related to
  *  window opening and other indoor information connected to the ventilation action*/

 /* Reporting the window angle*/
  Serial.println ("////////////////////////////////");
  Serial.println ("WINDOW");
    if (ang <= 45) { //If the condition is respected the value is indicated
  Serial.print("Opening Angle is ");
  Serial.print(ang);
  Serial.println("°");
  }else{
  Serial.println("Totally open"); //The else condition yields a "totally open" message
  }

 /* Reporting minutes to clean*/
  Serial.println("////////////////////////////////");
  Serial.println ("INSIDE");
  if (ang > 17 && ang < 45) { //Indication only when the window is open

    Serial.print ("Flow: ");
    Serial.print (Q);
    Serial.println(" m3/s");
    Serial.print("Minutes to clean: ");
    Serial.println(minleft);
  }else if (ang >= 45) {
    Serial.print ("Flow: ");
    Serial.print (Qt);
    Serial.println(" m3/s");
    Serial.print("Minutes to clean: ");
    Serial.println(minleftt);
```

```
 }else{
   Serial.println("Flow: ");
   Serial.println ("Minutes to clean: ");
 }
/* Reporting room comfort description*/
 if (Top <= Topli - 1.8){
   Serial.println ("Room temperature is very cold");
 }else if (Top < Topli - 0.8 && Top > Topli - 1.8){
   Serial.println ("Room temperature is cold");
 }else if (Top < Topli && Top > Topli -0.8){
   Serial.println ("Room temperature is slightly cold");
 }else if (Top > Topls && Top < Topls + 0.8){
   Serial.println ("Room temperature is slightly hot");
 }else if (Top > Topls +0.8 && Top < Topls + 1.8){
   Serial.println ("Room temperature is hot");
 }else if (Top >= Topls + 1.8){
   Serial.println ("Room temperature is very hot");
 }else{
   Serial.println ("Room temperature is comfortable");
 }

//INFO LINE 2: CENTRAL SECTION -----------------------------------------------------------------------------------
 /* The next code refers to the central section of the interface (WFB2) related to
  *  outside parameters (wind speed, wind temperature, humidity)*/

 /* Switching differential pressure sensors according to window angle*/
 if (ang>18) { //Separating wind measurements depending on opening
   windcond = vel1;
 }else{
   windcond = vel2;
 }

 /* Reporting wind speed description*/
 Serial.println ("////////////////////////////////");
 Serial.println ("OUTSIDE");

 if (windcond <= 0.2) {
 Serial.print("Wind is calm");
 }else if (windcond > 0.2 && windcond <= 0.8){
  Serial.print("Wind is gentle");
 }else if (windcond > 0.8 && windcond < 3.5){
  Serial.print("Wind is breezy");
 }else{
  Serial.print("Wind is strong");
 }

 /* Reporting wind temperature description*/
 if (25.9+3 >= Tout && Tout>= 25.9-3){
  Serial.println (" & pleasant");
 }else if (Tout < 25.9-5) {
  Serial.println (" but very cold");
```

```
 }else if (Tout < 25.9-4 && Tout > 25.9-5) {
  Serial.println (" but cold");
 }else if (Tout < 25.9-3 && Tout >= 25.9-4) {
  Serial.println (" & fresh");
 }else if (Tout >= 25.9+3 && Tout < 25.9+4) {
  Serial.println (" & warm");
 }else if (Tout >= 25.9+4 && Tout < 25.9+5) {
  Serial.println (" but hot");
 }else if (Tout >= 25.9+5) {
  Serial.println (" but very hot");
 }

/* Reporting relative humidity description*/
  if (rhout >=40 && rhout <= 60) {
   Serial.println ("Humidity is OK");
 }else if (rhout > 60 && rhout < 70){
   Serial.println ("Humidity is slightly high");
 }else if (rhout < 40 && rhout > 30){
   Serial.println ("Humidity is slightly low");
 }else if (rhout > 70 && rhout < 80){
   Serial.println ("Humidity is  high");
 }else if (rhout < 30 && rhout > 20){
   Serial.println ("Humidity is low");
 }else if (rhout <= 20){
   Serial.println ("Humidity is very low");
 }else if (rhout >= 80){
   Serial.println ("Humidity is very high");
 }

// COMFORT/DISCOMFORT SIGNALS ------------------------------------------------------------------------------
 /* The following code refers to the ranges when the LEDs are turned on or off*/

 /* Display is ON (white LED)*/
 if (dis1 < 60){
   digitalWrite(8, HIGH); // communicate user presence with led
   digitalWrite (10, HIGH); //Signal air is ok when user is near (no PM2.5 limit)
 } else {
   digitalWrite(8, LOW);
   digitalWrite (10, LOW);
 }

 /* Wind is comfortable (green LED)*/
  if (Tout <= 25.9+2.5 && Tout >= 25.9-2.5 && dis1<60) { //on only when user is near
   digitalWrite (9, HIGH);
  }else if (windcond > 0.3 && dis1<60){
   digitalWrite(9, HIGH);
  }else{
   digitalWrite(9, LOW);
  }

 /* Humidity is ok (green LED)*/
```

```
 if (rhout >= 30 && rhout <= 70 && dis1<60) { //on only when user is near
  digitalWrite (3, HIGH);
 }else if (rhout < 30 && rhout > 70 && dis1<60) { //slightly low/high is comfortable
  digitalWrite(3, LOW);
 }

/* Room is uncomfortable (red LED)*/
 if (Top >= Topls) {
  digitalWrite (2, HIGH);
 }else if (Top <= Topli) {
  digitalWrite (2, HIGH);
 }else if (Top < Topls && Top > Topli){ //slightly hot/cold is uncomfortable
  digitalWrite (2, LOW);
 }

//INFO LINE 3: BOTTOM SECTION -----------------------------------------------------------------------------------
/* The following code refers to the detail information (WFB3) showed at the bottom
 *  of the interface*/

/* List of selected values*/
 Serial.println ("////////////////////////////////");
 Serial.println ("OTHER OUTSIDE INFO");
 Serial.print("Tout: "); //temperature outside value
 Serial.print(Tout);
 Serial.print(" °C (Diff: ");
 Serial.print(Tout-Tind);
 Serial.print(")  ");
 Serial.print("Hout: "); //temperature outside value
 Serial.print(rhout);
 Serial.print("%  ");
 Serial.print("W: "); //temperature outside value
 Serial.print(windcond);
 Serial.println("m/s");

/*Future weather description*/
 if (1009.68 < P && P < 1022.14) {
  Serial.println ("Weather will be stable");
 }else if (P >= 1022.68){
  Serial.println ("Weather will be warmer");
 }else{
  Serial.println ("Weather will be cooler");
 }

/*Other information for barometric readings*/
//  Serial.print("Pressure: ");
//  Serial.print(P);
//  Serial.println(" hPa (ref:1009-1022)");

/*Other hidden and selectable information*/
//  Serial.print("User d: ");
//  Serial.println (dis1);
```

```
// Serial.print("Window d: ");
// Serial.println (dis2);
// Serial.print("Diff p1: ");
// Serial.println (pre1);
// Serial.print("Diff p2: ");
// Serial.println (pre2);
// Serial.print("Wind vel1: ");
// Serial.println (vel1);
// Serial.print("Cav: ");
// Serial.println (Cav);
// Serial.print("Uc: ");
// Serial.println (Uc);
// Serial.print("Top: ");
// Serial.println (Top);
// Serial.print("Tr: ");
// Serial.println (Tr);
// Serial.print("Topls: ");
// Serial.println (Topls);
// Serial.print("Topli: ");
// Serial.println (Topli);
// Serial.print("Tind: ");
// Serial.println (Tind);
// Serial.print("Tglass: ");
// Serial.println (Tglass);

  Serial.println('\n');
  delay(2000); //delay for all readings
}
```

MONITORING STATION (WALL DEVICE) //

```
//INCLUDING LIBRARIES ------------------------------------------------------------------------------------------
#include <Wire.h>
#include <SoftwareSerial.h> //Bluetooth
#include <Adafruit_GFX.h> //Thermocouple
#include <Adafruit_I2CDevice.h> //Thermocouple
#include <Adafruit_I2CRegister.h> //Thermocouple
#include "ClosedCube_HDC1080.h" //RH and Temperature sensor
ClosedCube_HDC1080 hdc1080; //RH and Temperature sensor
#include "Adafruit_MCP9600.h" //Thermocouple sensor
#include <K30_I2C.h> //CO2 sensor

//DEFINING SENSOR ADDRESSES -----------------------------------------------------------------------------
K30_I2C k30_i2c = K30_I2C(0x68); //CO2 Sensor
#define THERMO_ADDRESS (0x67) //Thermocouple
Adafruit_MCP9600 mcp; //Thermocouple
SoftwareSerial BTserial(2, 3); // RX | TX Bluetooth

int co2 = 0; //CO2 Sensor variables
int rc  = 1;
```

```
void setup() {
  Serial.begin(9600);

//SETTING UP CONTROL LED--------------------------------------------------------------------------------
  pinMode (10, OUTPUT); //Red led (high CO2)
  pinMode (12, OUTPUT); //Red led (high RH)

//SETING UP BLUETOOTH-------------------------------------------------------------------------------------
  BTserial.begin(9600); //Initializing Bluetooth shield

//SETTING UP RH AND TEMPERATURE-----------------------------------------------------------------------
  Serial.println("ClosedCube HDC1080 Arduino Test");
  hdc1080.begin(0x40); //Initializing RH sensor

  Serial.print("Manufacturer ID=0x");
  Serial.println(hdc1080.readManufacturerId(), HEX); // 0x5449 ID of Texas Instruments
  Serial.print("Device ID=0x");
  Serial.println(hdc1080.readDeviceId(), HEX); // 0x1050 ID of the device

//SET UP THERMOCOUPLE-------------------------------------------------------------------------------------
  while (!Serial) {
    delay(10);
  }

  /* Initialise the sensor with I2C_ADDRESS and the default I2C bus. */
  if (! mcp.begin(THERMO_ADDRESS)) {
      Serial.println("Sensor not found. Check wiring!");
      while (1);
  }

 /* Define type and resolution of the thermocouple */
  mcp.setADCresolution(MCP9600_ADCRESOLUTION_18);
  switch (mcp.getADCresolution()) {
    case MCP9600_ADCRESOLUTION_18:   break;
    case MCP9600_ADCRESOLUTION_16:   break;
    case MCP9600_ADCRESOLUTION_14:   break;
    case MCP9600_ADCRESOLUTION_12:   break;
  }

  mcp.setThermocoupleType(MCP9600_TYPE_T);
  switch (mcp.getThermocoupleType()) {
    case MCP9600_TYPE_T:  break;
  }
  mcp.setFilterCoefficient(3);
  mcp.enable(true);
}

void loop() {

// LOOP CO2, TEMPERATURE AND RH SENSOR ------------------------------------------------------------
  rc = k30_i2c.readCO2(co2);
```

```
 int co2r = co2 + 50; // value corrections from calibration
 float rhind = hdc1080.readHumidity()-6; // value corrections from calibration

// INFO LINE 1: CENTRAL SECTION -------------------------------------------------------------------------
/* The next code refers to the central section of the interface (WFB2) related to
 describing indoor parameters*/

/* Reporting air quality description*/
 Serial.println ("/////////////////////////");
 Serial.println ("INSIDE");

 if (co2 >= 1000 && co2 <=2500) {
  Serial.print("Air quality is ");
  Serial.println("Bad! ");
 }else if (co2 > 2500){
  Serial.print("Air quality is ");
  Serial.println("Very Bad!");
 }else if (co2 < 1000 && co2 > 700){
  Serial.println("Air quality is good");
 }else{
  Serial.println("Air quality is very good");
 }

/* Reporting relative humidity description*/
  if (rhind >=40 && rhind <= 60) {
  Serial.println ("Humidity is OK");
 }else if (rhind > 60 && rhind < 70){
  Serial.println ("Humidity is slightly high");
 }else if (rhind < 40 && rhind > 30){
  Serial.println ("Humidity is slightly low");
 }else if (rhind > 70 && rhind < 80){
  Serial.println ("Humidity is  high");
 }else if (rhind < 30 && rhind > 20){
  Serial.println ("Humidity is low");
 }else if (rhind <= 20){
  Serial.println ("Humidity is very low");
 }else if (rhind >= 80){
  Serial.println ("Humidity is very high");
 }

// DISCOMFORT SIGNALS ------------------------------------------------------------------------------------
/* The following code refers to the ranges when the LEDs are turned on or off*/

/* Air quality is bad (red LED)*/
 if (co2 >= 1000) { //From 1000 ppm is considered bad air
  digitalWrite(10, HIGH);
 }else{
  digitalWrite(10, LOW);
 }
/* Indoor relative humidity is high/low (red LED)*/
 if (rhind >=30 && rhind <= 70) { //Outside 30-70% range is considered bad RH
```

```
    digitalWrite (12, LOW);
  }else{
    digitalWrite (12, HIGH);
  }

//INFO LINE 3: BOTTOM SECTION ---------------------------------------------------------------------------
 /* The following code refers to the detail information (WFB3) showed at the bottom
  *  of the interface*/

 /* List of selected values*/
  Serial.println ("////////////////////////");
  Serial.println ("OTHER INSIDE INFO");
  Serial.print("CO2: ");
  Serial.print(co2r);
  Serial.print(" ppm  ");
  Serial.print("H: ");
  Serial.print(rhind);
  Serial.print(" %  ");
  Serial.println('\n');

 /*Other hidden and selectable information*/
//  Serial.print('\n');
//  Serial.print("Tind: ");
//  Serial.print(hdc1080.readTemperature());
//  Serial.println(" C");
//  Serial.print("Ts wall: ");
//  Serial.print(mcp.readThermocouple());
//  Serial.println(" C");

  delay(5000); //delay of all readings
 }
```

How can bioclimatic design foster diversification of low-energy building strategies in the next future? – Design for long-term learning process in residential buildings

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Abstract. In recent years, Bioclimatic Design theory recognized users' adaptive behavior a central aspect to address low-energy and comfort in buildings. Users that once were considered passive receptors of comfort, now are provided with the tools to make themselves comfortable. This paper takes a step forward, recognizing that users can be passive, reactive and creative at the same time. People often adopt complex behavior, construct proper habits or create new ones, considering their own culture and values. In this scenario, Bioclimatic Design should identify new strategies to promote sustainable behavior among final users. In this sense, knowing how inhabitants learn from built environment is the first step in this direction. Designers must adopt people perspective and identify how they relate to the built environment, receive information and act pro-environmentally. Surrounded by architectures that enable learning processes, inhabitants will be able to ethically balance energy sufficiency measures as a trade-off between energy needs reduction, unpredictable events, and individual growth. Conclusions highlight that to continue differentiating energy strategies, architecture and technology should broaden user choices and allow natural development of pro-environmental attitudes based on deep ecological culture and wellbeing.

1. Introduction

Improving building performances means better architectural design. Reducing energy consumptions also depends on how inhabitants interact with their surroundings. While humans are highly adaptive beings to such an extent that they can hurt themselves [1], their hedonistic behavior can satisfy comfort needs at the expense of the environment. Therefore, encouraging ecological sensitivity is a crucial aspect to balance energy consumptions and comfort inside the built environment. In this sense, in a society in constant transformation towards sustainability, how will R buildings support both individual growth and long-term pro-environmental behavior? This work is guided by this basic question to understand the end-user potential role in addressing sustainable concerns.

The present work is part of broader research that focuses on the impact of digital environmental information on learning processes in the architectural field. Therefore, it does not pretend to be exhaustive in its form, but to represent a theoretical input towards buildings with a more sustainable and human-centered lifecycle.

1.1. Structure of the paper

The paper consists of three different parts. The introductive part (section 2 and 3) describes the impact of people on building energy consumption and involves Bioclimatic Design theory in Low-Energy building strategies. Then, in the second part (from 4 to 7) users' long-term learning process is addressed, with a particular focus on sources of eco-information, usability and learnability of built environment following the example of cohousing design. Finally, in the last part (section 8) a case study is proposed, concluding with final comments (section 9).

2. Background

Buildings are one of the largest responsible for energy consumptions. Mostly it depends on how they are designed, informed, and used [2]. Understanding how people use buildings is an essential aspect for bridging the gap between design prediction and actual energy consumptions. Especially, pre-bound effects happen because households impose themselves to consume less in inefficient buildings [3]. For example, in Germany has been assessed a difference of 30% between 'real' consumption and predictions [4]. In the meantime, rebound effects happen when households live inside efficient buildings but tend to consume more [3]. In this case, efficient gains often lead to more consumption.

Involving or not end-users in energy problems depends on researchers' background and interpretation of sustainability. While some researchers suggest that constructing buildings less sensitive to people behavior is part of the solution [5], others argue that technology alone and stable conditions are unable to solve environmental concerns [6]. This paper considers that diversification of energy strategies allows people to build a more sustainable pro-environmental behavior based on greater engagement and a more shared ecological culture. To reduce the trend and achieve policy commitments, the whole society, architects and general inhabitants must be involved at the same level [2].

3. Importance of behavior in Low-Energy Strategies

In 2013 the International Energy Agency (IEA) recognized the diversification of Low-Energy building strategies, which include sufficiency, efficiency, and renewable energy measures [7]. While sufficiency address 'energy need' or the energy necessary for a specific end, like warming a room, cooking or lighting; efficiency is related to 'energy demand', which refers to the C energy required to run equipment and technological artifacts [8].

Considering Pricen (2005) sufficiency aims to 'enoughness' while efficiency tends to as much as possible with less. In other words, sufficiency address people behavior and foster energy needs reduction, focusing "on the switch, not the lamp" [9]. Fostering sufficiency measures enable inhabitant's choices towards a more ethical use of natural resources. Furthermore, sufficiency may indicate alternative design decisions, identifying configurations to implicitly guide users' behavior towards energy conservation. For example, one design decision could be collocating the stair core in the proximity of the entrance to discourage the use of elevators or making windows equally accessible and operable to people [10].

There is also an order in introducing energy measures. Sufficiency ones should come first to reduce energy needs before the introduction of more sophisticated technologies [11]. For instance, in the Mediterranean region, buildings should be designed first with the aim to capture and store solar energy, and only if required, to support the design with mechanical systems [12]. Consequently, sufficiency measures naturally connect with the central idea of Bioclimatic Design.

Defining Bioclimatic Design perspective

The IEA indicates Bioclimatic Design as sufficiency measures to minimize building consumptions [7]. It is a human-centered approach strongly correlated with regional climates and cultural differentiation. It claims that architecture should be linked to the local microclimate and aim for energy savings while maintaining comfort for the inhabitants. Considering the definition of the Architecture Institute of Japan (2010), it is an "architectural design that conforms to the nature of the area and can maintain the global environment comfortable and pleasing to human beings" [13]. Moreover, at the center, there are user's consciousness and behavior, and architectures should allow interaction with buildings through 'life-size' technologies [13]. In other words, its main scope is to provide inhabitants robust and accessible technologies towards comfort balance and energy reduction, mostly deploying sufficiency measures.

4. From passive to creative behavior of inhabitants

How to provide comfort to people has conceptually changed over time. From the notion of 'shelter' against the exterior environment of the first theories [14] and "comfort as a right" [15], to the adaptive behavior of inhabitants, who are given the tools to adapt to reach thermal comfort goals [16].

Interest in adaptive comfort has grown exponentially since the 1990s (132), culminating in the PLEA-2009 Québec Manifesto, where it was recognized "the role of inhabitants as a key 'active' determinant of energy performance in 'passive' design, through adaptive opportunities" [17]. Particularly, it expressed various directives to improve performance in buildings. While *Directive 1* (Community context) express the necessity to adopt a multiscale approach to improve performance of building [15], *Directive 2* (Provision of adaptive opportunities) suggest realizing buildings with several adaptive opportunities. However, to support long-term learning attitudes providing end-users with different adapting tools does not guarantee ecological choices. Furthermore, it does not represent the complex nature of human behavior.

In real life context, the behavior is difficult to predict. While passive occupants do not alter their conduct, and 'adaptive' users react assuming the instruments given by designers, 'creative' inhabitants also encounter new meanings and alter space functions. In other words, according to Hill (2003), whose book helps to illustrate the nature of actions in architecture, people can learn new habits or modify the previous one considering newly acquired knowledge. Moreover, "passive, reactive and creative use can occur together" [18] (see 'figure 1'). For example, passive use can be encountered in a factory or during a wedding ceremony [18], but especially inside R buildings, people "leaves doors open, generate body heat, keep tropical fish tanks and install plasma TV screens" [2]. Consequently, to support creative use, design strategies based on learning are needed.

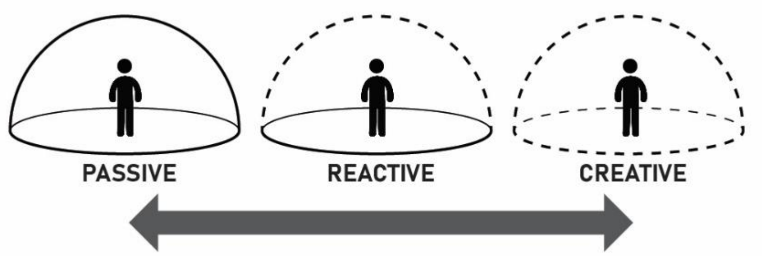

Figure 1. From passive to creative inhabitants' behavior occurring at the same time.

To address not only energy consumption issues but also long-term sustainability, people should learn gradually. Authors consider that short-term environmental attitudes based on extrinsic motivations do not last, and that sustainability requires a long-term commitment [19]. For instance, van der Linden (2015) concluded that long-term motivators are needed. In fact, in her case study, during a nationwide energy reduction competition among university students, electricity consumption effectively decreased over a month (the length of the event). However, about ten days after the experiment consumptions returned to normal [19]. Consequently, the case suggests that technology is not enough and that the learning process within the built environment should enrich the ecological culture of the whole society.

1.2. Learning process in Bioclimatic Design

From a Bioclimatic Design perspective learning process embrace the local environment, culture, and experience. In this respect, Guy and Farmer (2001) proposed to redefine sustainable architecture considering six interpretation, representing as many different sources of knowledge. The author distinguished the technic, centric, aesthetic, cultural, medical and the social perspective [20].

Even if the authors do not directly express it, it is inside the eco-cultural interpretation that Bioclimatic Design is collocated. As the authors illustrate, in such a concept of place human beings learn how to 'dwell' based on buildings that reflect the local cultural landscape and bioclimate [20]. In other words, comfort and energy reduction depends on learning from the local environment.

Outside strict categorization of sustainable design approaches, this paper will collocate Bioclimatic Design inside a broader interdisciplinary context taking inspiration from the holistic approach proposed by Moore and Karvonen (2008). In their study, Guy and Farmer's competing interpretations are utilized depending on different context and situation [21]. Therefore, Bioclimatic Design starting from the eco-cultural basis may adopt and collaborate with different 'sustainable interpreters' depending on where eco-information come from (see 'figure 3'). In this context, the next part illustrates how inhabitants' learning process may be supported by nature, architecture, technology, and community to 'bridge' the gaps between acquired information, concern and pro-environmental behavior.

5. From eco-information to pro-environmental behavior

Defining the process aimed at direct and indirect pro-environmental behavior is a complex task. Generally, people access information from a source, elaborate individual concern through learning, and then act pro-environmentally. However, over time environmental psychology and information studies have long studied the presence of 'behavioral gaps' and barriers between individuals and their conduct [22]. In 'figure 2' the information gap (gap 'a') indicates that individuals absorb not the totality of relevant information while the action gap (gap 'b') indicates that individual concern does not necessarily lead to environmental attitude due to barriers that hinder people positive responses [22]. Finally, eco-feedback represents the information proceeding from monitoring technologies and other digital tools.

In relation to the extent of the present work, external factors affecting actions and behavioral models aimed at explaining the knowledge-concern-action paradox [23], the latter widely studied in environmental psychology, will not be treated. Consequently, following the "figure 2" scheme, the primary sources of eco-information will be analyzed, proposing a general framework that identifies the role of architecture and technology concerning them.

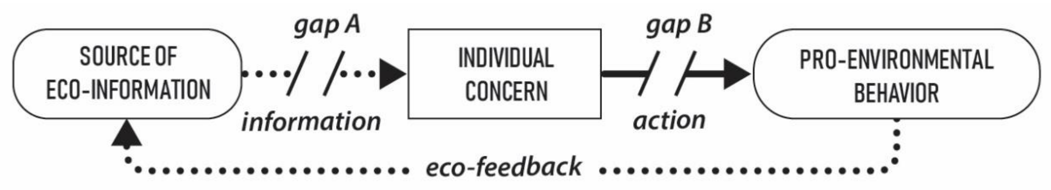

Figure 2. The process toward direct pro-environmental behavior.

6. Engaging end-user towards pro-environmental behavior

Sources of ecological information are the initial step towards pro-environmental behavior. Involving a broad context, social environment and interaction are the first dimensions that influence people behavior towards ecological actions [24]. Ian McHarg is considered a reference author in recognizing the positive (and negative) impact of collective choices towards the natural environment, preparing the foundation of what would then become landscape architecture [25]. Starting from his perspective, the community landscape theory of Mainzer and Luloff (2017) affirms that behavior, landscape, and local community form the basic interdisciplinary structure of pro-environmental actions at large scale [26].

Considering this field of interaction and the eco-cultural perspective adopted by Bioclimatic Design, a broad picture of eco-information, which can lead to a trend towards reducing consumption and inducing environmental behavior, has been identified. The 'dimensions' that constitute the framework are described in the points below.

The 'Bioregional and social' level

The bioregional and social level represents the background of the framework. On the one side, the Bioregion represents a combination of natural, ecological and biological elements [20]. Nature and ecology themselves represent a primary source of eco-information. Depending on the context, architectures generally integrated with living nature can produce respect for nature [27]. Besides, many researchers focused on biophilia recognize positive psychological effects on behavior [28]. To the other side, collocated at the same level, there is the society, where education, norms, and policies can support general environmental concern. Inside the 'bioregional and social' level it is possible to recognize three 'dimensions' of eco-information: the landscape, which is a combination of physical and cultural attributes; the community of people, different from general society; and the individual.

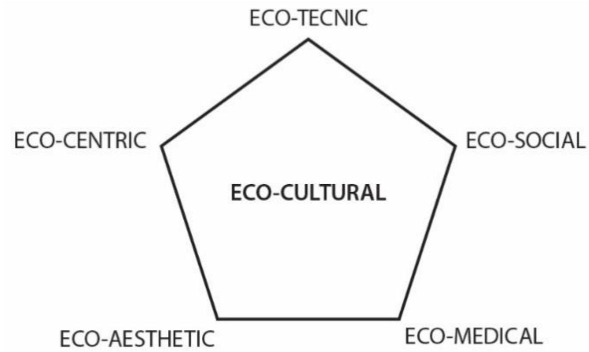

Figure 3. Eco-cultural interpretation as the central focus of a holistic approach to sustainable architecture.

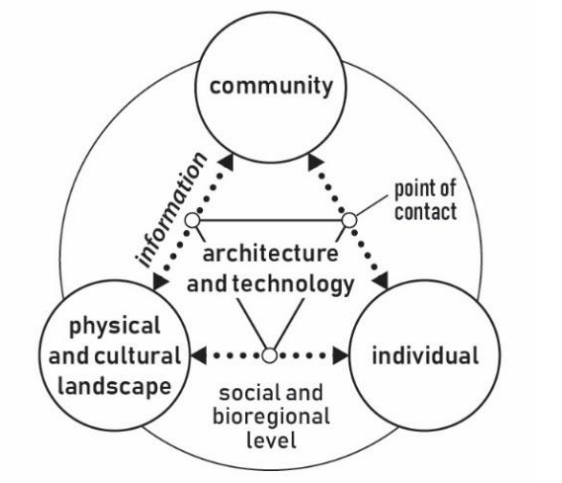

Figure 4. Architecture and technology should connect individual to community, landscape, and bioregion to foster learning processes.

The 'Landscape' dimension. Bioclimatic Design seeks to preserve cultural diversities connected to the local landscape, whose physical properties interact with the culture of the place [20]. The landscape physically reflects the values of the place and the environmental activities of the local society [26]. In other words, eco-information may come from the interaction between local settlements and the natural environment.

The 'Community' dimension. It represents the network of association constructed around individuals, and it is not referred to any precise scale [26]. Much of the information may come from the family or the clan that forms direct social connections [29], from co-workers or neighbors. Apart from social and cultural bound, seeing people acting positively may induce to imitation. For example, in a study related to household energy conservation in California, Nolan et al. (2008) demonstrated that even if people declared not to be influenced by neighborhood behavior, witnessing them resulted in manifested pro-environmental actions [30].

The 'Individual' dimension. Apart from being the one directly connected to pro-environmental actions, individual reflects cultural values, share environmental knowledge, and influence other people through indirect participation to environmental activities [22] or his direct behavior. Therefore, an individual is considered a potential source of eco-information.

7. Reducing behavioral gaps in the built environment

The framework described above individuates the basic condition that architecture, supported by technology, should establish points of contact between the various levels and different dimensions. In other words, not to constitute a barrier to the potential flow of eco-information. Furthermore, a typical example of a facility that has been designed to provide an ideal environment for interactions between the individual and community is cohousing [31]. Consequently, in the following text, to illustrate the design consequence of the proposed framework regarding social interaction, cohousing is described as the ideal solution.

Cohousing as ideal learning environment

Cohousing communities are R settlements of generally 10-40 houses, where inhabitants intentionally agree to share living spaces and construct a group of individuals that support themselves towards wicked social aims like ecology, sustainability, poverty, and housing access. According to the Cohousing directory, currently there are 165 established communities in the US (with forming 140) [32]. Others nations with a consistent number or cohousing are Denmark, UK, and Australia [33][34]. Cohousing, like other grassroots initiatives such as ecovillages, low impact dwellings, and collaborative housing intend to foster interpersonal connections, social contact, and to promote pro-social and pro-environmental behavior at the same time [35]. Typically, cohousing considers at least 4 'design modalities' to foster pro-environmental behavior:

Usability and robustness of systems. The framework describes a bottom-up approach where end-users are co-producers of knowledge, along with 'design experts'. According to Manzini (2016), in a society gradually concerned with sustainable issues, general people are rediscovering the power of interaction and creative collaboration, also thanks to enhanced digital communication. Grassroots initiatives like cohousing represent this trend. In such complex environment, the distance between designers (interpreters) and creative communities is reduced, and design research, as well as its products, should be accessible to co-produce learning among different subjects [36]. Therefore, the built environment should be characterized by usability and robustness from the perspective of end-users. Usability aspects are commonly analyzed by HCI research and have been recently recognized in architectural design practice. According to Dalton et al. (2016), "[usability] is the capability of the building to be understood, learned and liked by the user, when used under specific conditions" [37]. Typical usability issues regarding mechanical systems are wrong labelling, inaccessibility, poor or complex interactions, which in facilities led by general public it may become frustrating [38].

Adaptive solutions and 'sense making' are considered together. To solve the complexity of energy reduction, the choice between several solutions should be supported by meaning. Interacting with people of the same community brings their daily experience so that to indicate the best adaptive solution, but also in defining its impact based on shared ecological values [36]. Diffused and locally generated knowledge is then part of daily life and constantly inform adaptive choices.

From individual to social learning. In this respect, Wilner et al. (2012) describe social learning as the process inside cohousing. Social learning occurs 'when we share our experiences, ideas, and environments with others' [39]. It is composed by a distinct moment of reflection: the *Single Loop Learning*, which addresses individual habits; the *Double Loop Learning* which is directed to intentions and considers interaction with others; and the *Triple Loop Learning*, which is dedicated to correct governance and procedures and is enabled in participative events. At the design level, each of those reflections is normally translated in physical spaces and scheduled inside the community.

Design for social connection and interaction. Cohousing design try to promote formal and informal encounters in shared spaces. In this sense, it generally analyses aspects like proximity of the housing units and their position considering neighboring houses, the features of the common room, shared pathways and surveillance given by the same members of the community [31]. The next text will present a case study of co-housing made by Stevenson et al. (2016), who illustrate the theoretical content exposed until this point.

8. The ‘LILAC’ case study

LILAC, the acronym of Low Impact Living Affordable Community, is a renowned urban-based cooperative project developed in Leeds UK, opened to residents in mid-2012. This low-carbon neighborhood consists in 20 straw-bale homes, plus 1 common house, welcoming 45 people of different ages (from 10 to 70 years old), occupation and family dimension (see ‘figure 5'). During the design process, led by residents with the help of an energy consultant, general energy criteria were defined. Among them, there were low impact, future proof, comfortable, learning, easy to use and maintain, affordable, understandable and demonstrable [34]. To meet CSH level 4 and general needs of the community were installed PV array, mechanical ventilation units with heat recovery (MVHR), high-efficiency gas boilers with solar thermal water-heating system, among others (see ‘table 1') [34].

Figure 5. View of the common building, the shared laundry on its right, the pond and other community spaces of LILAC neghbourhood.
(Source: https://makinglewes.org/2014/01/30/lilac-affordable-ecological-co-housing-project-leeds-uk/)

Figure 6. Interior view of the residence and typical operable windows with multiple openings.
(Source: http://www.bath.ac.uk/research/news/2013/12/12/straw-cuts-energy-bills-by-90/)

Learning co-production in LILAC

Conceptually, the project is a tentative to organize and anticipate what it might be a society free from fossil fuels, low-carbon and energetically managed with a bottom-up approach. Special effort has been dedicated to creating learning opportunity through extra redundancy and to give inhabitants the instruments to cope with unpredictable events.

In this sense, Stevenson et al. (2016) have recognized two kinds of redundancy in LILAC, which are intended to promote learning process: physical redundancy (technological and spatial) and social redundancy (from the local community) (see ‘table 1'). According to the authors, redundancy is considered the component to ‘translate adaptive capacity into action’ [35].

First, spatial redundancy permits to create information exchange between individuals, community, visitors, and expert occasionally visiting the neighborhood. Furthermore, it gives people choices regarding their adaptive behavior. For example, houses configuration allows internal migration according to the moment of the day and season, thanks to multiple orientations of houses. In the meantime, the presence of exterior pond and gardens provide cool areas during summer seasons [35].

Second, technological redundancy gives inhabitants the possibility to select the best tools for their comfort, depending on previous experiences, renewable energy availability, technical malfunctions or misunderstandings. For instance, the learning process regarding microtechnology of the MVHR system has produced concerning. From the initial technician's advice of maintaining the unit always operative, inhabitants learned to switch it off alternating instead windows opening behavior and natural ventilation, considered healthier and more ecological. According to Stevenson et al., this multiple ventilation feature is given by the high operability of windows, which is not common in this kind of projects (see 'figure 6') [35]. Additionally, the researchers individuated 17 different adaptive behavioral patterns between MVHR and window systems depending on weather conditions (see 'figure 7') [35].

Table 1. Different kind of redundancy in support of social learning processes inside LILAC.

kinds of redundancy		
technological	**spatial**	**social (community)**
• Electricity from the national grid • Back up electric immersion heaters • PV and solar thermal panels • Wood stove (common house) • Separated water system (common house) • MVHR system • Multiple window openings	• Typical private houses • Common refuge • Common kitchen • Common living spaces • Common pantry • Separated laundry space • Central pond and garden • Central allotments (vegetable production)	• Inhabitants of various ages (different time availability) signing a common agreement • Selected 'maintenance task team' • Selected 'technology learners' • Mutual Home Ownership Society (MHOS)

Figure 7. Behavioral patterns between windows and mechanical ventilation system inside LILAC. (Source: Stevenson et al.)

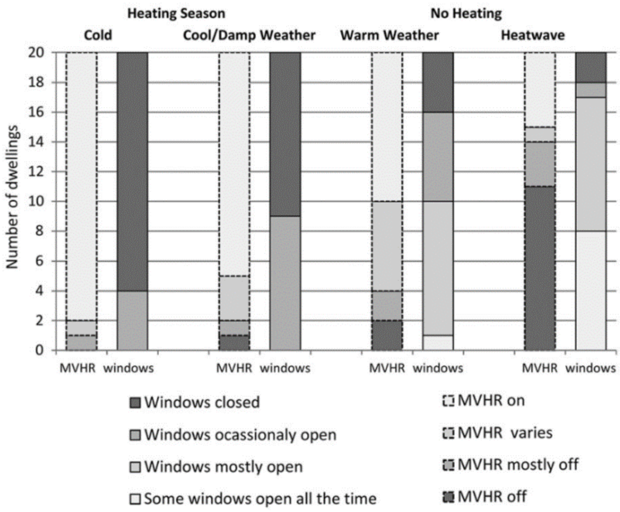

Table 2. Learning co-production and information flow inside LILAC.

Learning process of end-users	**Modality of information flow**
Individual learning (single loop)	• Trial and error
Peer-to-peer (interactive)	• Casual conversation • Researchers visits • Online tools (SNS and forums)
Collective (interactive and/or general redefinition of governance)	• Community notice board • General bimonthly meetings • Local and national events

Third, community redundancy is what permits different kinds of learning, from strictly individual to collective. As previously illustrated, different reflections are applied in order to promote social learning. For example, apart from individual learning (trial and error) guided by direct feedback, casual interactive conversation, and peer-to-peer learning may take place in the common laundry or at the doorstep. At the meanwhile more profound information and general participation regarding main governance can be performed, for example, during bimonthly meetings or local national events (see 'table 2'). In this scenario, among other figures, 'selected inhabitants' are dedicated to learn and access new technologies and to share their knowledge to other members, while the role of the 'maintenance task team' is to manage incidents and arrange the required repairs [35]. In other words, given that few systems (especially innovative and hi-tech) are readily accessible or 'smart' from the point of view of users, social learning is important for optimal use, but it may be not enough. Once the system is in place, it should not constitute a barrier to the learning process of inhabitants.

9. Discussion and concluding comments

People already know their impact on the natural environment, but there are barriers and gaps in the information process that hinder pro-environmental actions. In the next future, along with the efficiency of technological advances, Bioclimatic Design will be able to foster diversification allowing 'creative' inhabitants to find their path towards pro-environmental behavior through long-term learning processes and interaction with local community and landscape. In this scenario, the ideal example provided by ecological cohousing and the framework of source of eco-information indicate various design aspects to consider at the time of involving 'creative' end-users and communities. Among others: 1) Aiming at co-produced learning between individual and sources of eco-information; 2) Designing for social contact; 3) Multiple orientation of buildings; 4) Social and physical redundancy; 4) Extending human-building interaction outside private spaces; 5) Providing usable and robust technologies; 6) Differentiating learning times and participation; 7) Supporting adaptive solution with shared values.

To conclude, although cohousing initiatives are far from being easy to construct and manage, with issues regarding the up-scaling of their practices, they represent a clear example of bottom-up and long-term gradual approach towards a more diffused ecological culture. Furthermore, inside cohousing, digital tools play an essential role in shortening communication distances and triggering collective actions. But because of their inner organization, technological innovation must be carefully integrated into the built environment not to generate detachment between the individual and other significant sources of ecological information.

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Identifying the Right Climate Scale to Support Low-Energy Building Design Process

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Abstract

To be concretely smart, low-energy buildings should be able to interpret climate and contextual information around them. In this respect, low-energy buildings are gradually relying on databases to justify environmentally driven decisions. However, this growing tendency in research and profession raises new questions regarding analysis and design process in architecture. In fact, considering low-energy building as a sum of different energy strategies, not all of them can be defined by homogeneous source of information. For example, energy sufficiency strategies, which lead to energy needs reductions and involve people behavior, require a significant "change of scale" regarding environmental simulations and justification of design decisions.
In this respect, Bioclimatic Design principles connect built system with geographic, climatic and cultural context and people adaptive behavior. Therefore, it generates ambiguity in selecting the right scale of space-time information. On the one hand, energy simulation regarding microclimate data are interpreted by CAD/BIM based software and holds object-oriented information. On the other hand, GIS based software extends project boundaries to embrace local and regional dimension showing, among other things, topography or trees position and growth. From literature, BIM/GIS integration is a growing field of interest but what is unclear is how climate information is integrated inside Bioclimatic Design processes and what kind of background information would support the discipline in the next future.
The purpose of this paper is to define time-space extension of information regarding Bioclimatic Design approach, a main step towards low-energy and context-sensitive buildings. To do so, we will reconsider the discipline from the perspective of "database thinking" and architects' point of view inside the design process. It will be useful to identify kind of data, main strategies and configuration of process, to have the whole picture of the Bioclimatic Design discipline inside an always growing digital environment.

Keywords: Climate Data, Design Decisions, Monitoring Systems, Bioclimatic Design, Scale

1. Introduction

Interpreting climate is an important aspect in our society. Many researchers and professionals in construction field analyze climate to diminish energy consumptions and improve comfort in built environments. Inside this process, a recognized method to translate climate information in built environments is through the adoption Bioclimatic Design principles, which are considered an important step towards low-energy and carbon reduction in built environment (IEA, 2013). Particularly, if we observe Bioclimatic Design conceptualization during the early 50's, it was already recognizable an approach based on data research, visualization and communication, that continues today under the process of digitalization of information.

Software are gradually improving their performances and usability. Mainly due to their advances, architects and design teams can now gradually access climate information, but they should be aware of how data are collected, and what affects climate data accuracy. In fact, digital tools have the potential to revolutionize passive approaches and to close the gap between architectural and engineering design process (Omidfar and Weissman, 2012), yet design teams should always adopt an inquisitive mindset to recognize source of problems. In this sense, critical aspects could be generated by accessing contextual information at different space-time scale, as it is typical of Bioclimatic Design initial process, which consider a pre-design research to inform later decisions.

1.1 Paper content and main terms

This paper is part of a larger study that intend to assess the impact of digitalization of information and digital tools inside sustainable building design. Although, the author is aware of cross-scale implication around climate aspects, the content of the paper is limited to analyze climate data referred to space-time scale and its way to alter early design decisions. Furthermore, given that architects should access climate data early within design process, it is not considered data for detailed simulations, which are normally performed during advanced phases.

It is important, at this point, to clarify some terms applied in the paper. First, with Bioclimatic Design is intended a low energy approach that translate climate information in architectural configurations. Its main scope is to reduce energy needs providing inhabitants the means to reach comfort balance. Second the term 'scale' is after Wentz et al., who consider it "the level of detail and scope needed to address questions or problems that are critical to planners and decision-makers" (Wentz et al., 2012). Consequently, architects and design team interface with climate information at different time-scale, to construct proper knowledge during design process.

2. Importance of climate in low-energy building design

2.1 Architect's role and importance of early information

Architects' role is decisive to introduce climate information inside design workflow. According to DeKay, who refers to Front Loaded Sustainable Design, it is during the initial phase that design decisions can be easily adopted and have the highest environmental impact (DeKay and Brown, 2014). Furthermore, architects have the responsibility to manage complex array of issues, and to integrate climate information with other design constraints. In this sense, compared to 'traditional' design process, Bioclimatic Design principles increase project complexity side by side with other design constraints, which comes from different sources and directions.

In Bioclimatic Design, climate aspects are considered external constraints. Most of the time, between designers and users there is a gap given by project type, as happens for example with schools (Lawson, 2005). In this context, the complex task for architects is to reduce energy needs for paying clients, energy consumption for the environment, but also to guarantee accessibility to thermal comfort by users.

The rigidity of all these constraints is normally managed through integrated design solutions, which depend on the harmonious work between resources, for the best possible results. In this sense, the International Energy Agency in 2013 promoted an innovative approach to energy policies suggesting that the path towards energy reduction is achievable integrating three strategies: energy sufficiency (where Bioclimatic Design stands), energy efficiency and the use of renewable energy (IEA, 2013).

Furthermore, individuals or Design Simulation Groups (DSG) dedicated to context analysis, need to access right quantity of data at the right time without affecting collaboration. Besides interfacing with clients, architects should be able to work with other professionals involved in environmental analysis, such as ecologists, anthropologists, geographers, etc. and visualize climate information combined with other sites attributes. For example, in case of more complex pre-design phases, physical, biological and geographical attributes may be mapped to be gathered in GIS software (LaGro Jr, 2001) and used simultaneously with BIM/CAD interfaces (Schaller, 2017).

2.2 Climate data access and bioclimatic design strategies

Accessing climate information for non-scientists is still unclear and poorly coordinated. An effort to gradually eliminate barriers between climate scientists and users involved in decision-making, together with a general coordination of informatization, comes from the Global Framework for Climate Service (GFCS) inside WMO reports in 2014 (Graham et al., 2015). In Figure 1, it is illustrated the framework from the point of view of architects and design teams adopting Bioclimatic Design strategies.

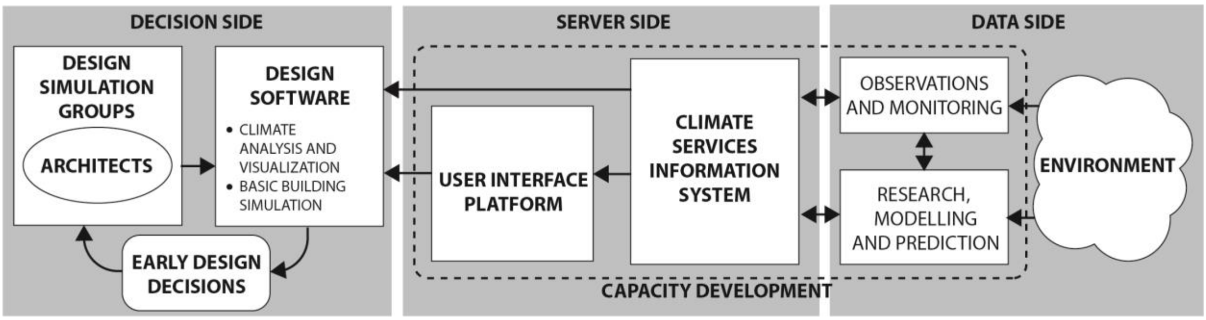

Figure 1: Accessing climate data for early design decisions

Looking at the decision side, architects, individually or inside DSG, adopt climate visualizations and basic building simulations. They can access climate data directly from climate services like public or private agencies or via User Interface Platform (UIP). As proposed by the GFCS, in the next future UIP will be considered the bridge between providers and end users to better address their needs (WMO, 2014). Main climate data are temperature, humidity, radiation and air movement, and from them secondary data can be derived (Olgyay and Olgyay, 1963; Szokolay, 2004). Subsequently, climate data inform design decisions depending on preliminary tools like the 'bioclimatic chart' that connects thermal comfort to design strategies such as passive solar heating, natural ventilation, thermal mass, evaporative cooling, among others (Yang, Lam and Liu, 2005). Additionally, there are on-site and off-site analysis for energy programming and site selection and numerous detail strategies depending on scale, from city to building parts. Just as example, Table 1 indicates common solar design strategies at building scale, which are also adopted by the case study illustrated in this paper.

Table 1: Common solar design strategies at building scale (adapted from Hui et al., 1997)

Design aspect	Examples of design tasks	Climatic data required
Solar design strategies	• Shading and sun control • Passive solar design • Solar thermal and photovoltaics design	• Solar path and position (charts) • Temperature and solar radiation • Sunshine duration and cloudiness

2.3 Interactions between climate scales

Climate is normally described using space-time scale and such distinction is useful for design purposes. Linacre (1992) separates climate in microclimate, topoclimate, mesoclimate, synoptic and global climate, indicating that the atmosphere of an area depends on the average of climates at the next smaller scale and on the overriding effects of the environment provided by the scale right above (Linacre, 1992). This 'linearity of interaction' can also be found in Bioclimatic Design theory (Givoni, 1998). However, from the point of view of site analysis, constructing knowledge regarding climate at larger scales is relatively easy compared to what happen at local scale (Raschi, Conese and Battista, 2016).

For universal knowledge designers can access bioclimatic maps, general publications or consulting the Internet. Particularly, bioclimatic maps have been recently redeveloped by Rivas-Martinez et al., and provide a general idea of environmental patterns at continental scale, with the possibility to reach regional scale. This information directly visualized in spatial maps are ideal to easily understand what kind of climate can be expected in different areas, being able to anticipate early design decisions. However, as happens in other fields like urban climatology and agronomy, reaching local knowledge is laborious and require the combination of different methods. For example, inside cities, urban canopy, surface temperatures, building disposition, wind advection, anthropic heat production and air pollution characterize the climate, which changes according to location. The climate variates even outside cities, where the presence of large bodies of water, forests, and topographical features, among others, have big local impact.

3. Generating local knowledge for design decisions

3.1 Methods to investigate the climate

Current methods to quantitatively investigate the climate for design aspects can be classified in three different groups.

The main method to collect data is through observation, which comprehend ground sensing and remote sensing. On the one hand, ground sensing refers to meteorological station ("principal" or "synoptic") that collect weather data making surface observation and can furtherly be distinguished in manual or automated stations (World Meteorological Organization, 2014). Typical information of meteorological stations are Dry bulb Temperatures, Wet-Bulb Temperatures, Relative Humidity, Wind velocity and direction, Sunshine Duration, Cloud Cover, Rainfalls, Solar Irradiation. Furthermore, there are minor monitoring systems like specific and mobile station that are generally dedicated to record specific phenomena. Examples of recent mobile application are on vehicles (Coutts et al., 2016), drones (Marschall, Ninsalam and Burry, 2018), as wearable sensors to aggregate climate at living level (Pigliautile and Pisello, 2018) or as portable instruments for diagnosis. On the other hand, Remote Sensing can be divided into satellites and airborne. These methods take images of the Earth from above and depending on their spectral resolution can provide thermal, infrared, visible and panchromatic images (Patino and Duque, 2013). Their outputs are Land Surface Temperatures, air composition, thermal infrared analysis, radiance values, among others, all widely used in urban climatology and agriculture. Furthermore, there are UAV/Drones which are increasingly adopted in urban applications and mapping (Norzailawati et al., 2018).

Other methods to collect data are by synthetization of historical weather data, and through elaboration of Climate Models. The first one, namely weather generators (or 'virtual' station) were born to imitate sensed data and to extend data coverage of 'physical' stations. The second one, Climate Models, are complex algorithms dedicated to deliver long-term and climate change predictions (NOAA, 2017). They can be divided in Global Climate Models (GCMs) and Regional Climate Models (RCMs) and while GCMs remain at national level, RCMs can reach scales of 10 km or larger (the size of big cities) utilizing downscaling techniques (Herrera et al., 2017).

3.2 Current advantages and limits of different methods

From architectural perspective it is convenient to divide above techniques into punctual and multidimensional methods. While punctual methods are referred to build weather datasets of specific point in time and space, multidimensional ones allow to integrate climate aspects with geospatial information, important to generate holistic knowledge and help collaboration among different professionals. On the one hand, data from 'physical' weather station are considered the most reliable and traceable. On the other, multidimensional methods support the other techniques and reach remote zones. Particularly, multidimensional methods collocate climate information into space, which is critical for design decisions. For example, they show land cover and land use, discover relation between human and environment, or evaluates the effect of space-time changings of cities, among others (Wentz et al., 2012). Particularly, drones can be cost-effective compared to satellites or aircrafts and give real time climate and visual information of precise areas (Norzailawati et al., 2018). To continue, in Table 2, current limits of four main methods are listed.

Table 2: Different methods of climate data collection and current limits

Punctual methods		**Multidimensional methods**	
'Physical' stations	**'Virtual' Stations**	**Satellites**	**Aircrafts/UAV/Drones**
• Relatively few and unevenly distributed • Different data depending on recording periods • Using coastal or airport data for sites inside the city • Unable to predict future weather or climate change	• Assuming future prediction based on historical statistics • Synthetic data • Traceability of data • Risk to easily mislead designers • Often accessing data is paid	• Difficulty in representing urban or local phenomena • Poor time resolution and periods • Difficulty in integrating outputs with other geospatial data	• Costly solution (especially Airborne) • Poor time periods • Time consuming methods • Difficulty in integrating outputs with other geospatial data

3.3 Ideal data for design decisions

Selecting the proper weather type depends on design purpose and project situation, and careful attention should be taken in choosing them. The most common weather data types are the TRY (Test Reference Year), the TMY (Test Meteorological Year), the UK TRY, the IWEC (International Weather for Energy Calculation) with location throughout the world, and the WYEC (Weather Year for Energy Calculation) developed by the ASHRAE. But despite this complexity, most of them adopt the .EPW (Energy Plus Weather) format, which has become common in building software.

For building design, many authors indicate Typical Meteorological Year (TMY) as the most appropriate for evaluating long-term behavior of buildings, mainly because it represents an average of long historical records of at least 10-30 years (Crawley, 1998) and considers more variables compared, for example, to TRY (Herrera et al., 2017). Extreme weather files, instead, are better for sizing equipment and more apt for mechanical engineering, yet it is still important to consider extreme weather examples inside datasets, being that such events will increase in the next future. In this respect, Herrera et al. have recently descripted seven 'technical ideal features' for building design. Particularly, they should contain example of typical, extreme and future conditions; be at the right temporal resolution required by software (hourly or more); representing the local topography of the project and considering the effects of urban microclimate; and finally, they should be traceable (Herrera et al., 2017). These points clearly meet architects' requirements, but most authors in architectural field are also concerned by other important factors, which are common during initial design phase. On the one hand, it is easy to get trapped by over-precision of data and information during design flows (Lawson, 2005). This concept is clearly expressed by Szokolay (2004), suggesting that, for example, in a right balanced representation of early climate data, visualizing hourly temperature for a typical year (8760 items) it is unnecessarily detailed, and that monthly means of daily maxima and minima may be better (Szokolay, 2004). On the other hand, affordable access to data might be another important point for design teams. In fact, clients may not spend resources in collecting high quality and expensive contextual information (including climate), especially during initial design stages.

Considering the above, ideal climate data for early design decisions should consider further aspects based on architects' workflow. In Table 3, the ideal points are listed indicating which of them are important or decisive for tight design schedule, affordability, and coarse level of detail typical of beginning processes.

Table 3: Ideal technical features of climate data considering early design decisions

Ideal technical features of data	Early design decisions
Containing examples of extreme conditions	Important
Right temporal resolution for design software	Important
Containing examples of possible future climates and the effects of climate change	Important
Containing typical climate conditions	Decisive
Considering effects of urban microclimate	Decisive
Representing project locality	Decisive
Credibility and traceability of data	Decisive
Balancing between affordability and accessibility	Decisive
Balancing between preciseness and accessibility	Decisive

3.4 Case study analysis

Afterwards, it is analyzed a case study of Social Housing in Milan conducted by Erba S., Causone F., and Armani R., in 2017. It has been selected given the correlation with several aspects exposed in this paper. Particularly, it represents the lack of examples of extreme conditions inside weather data files, demonstrating how it affects Bioclimatic Design strategies.

The case describes the refurbishment of a social housing district in Milan. The main purpose of the project is to ameliorate energy performances given the current low standard of the buildings. To achieve the goal, among different strategies proposed by the Municipality of Milano there are energy needs reductions such as collocating exterior insulation covering horizontal and vertical partitions, improving performance of windows (with low-e double glazing and better frames) and collocating exterior solar shading. Particularly, the city of Milan is covered by five different weather datasets provided by various sources. In *Table 4* are listed the 5 datasets, their sources, collecting method and period of record.

Table 4: the different climate datasets considered in the building energy evaluation

Name	Source	Method	Period of record
MI_Linate_1951-1970	IGDG (Gianni De Giorgio)	Physical record	1951-1970 (19 years)
MI_Malpensa 1982-1999	IWEC (ASHRAE research project)	Physical record	1982-1999 (17 years)
MI_Linate_1961-1990	Meteonorm (Weather Generator)	Synthetic weather	1961-1990 (29 years)
MI_Linate_2000-2009	Meteonorm (Weather Generator)	Synthetic weather	2000-2009 (9 years)
MI_City_2006-2015	EMCWF and satellite data (CM SAF)	Climate model	2006-2015 (9 years)

The results of the comparison show unavoidable discrepancies especially regarding heating requirements. The general distribution of average monthly temperatures has been considered regular despite differences of 5 °C between the different sources. The same opinion is given analyzing Monthly Global Horizontal Radiation, with a difference of 30 kWh/ (m2 month). However, in *Figure 2*, comparing Heat Degree Days (HDD) and Cold Degree Days (CDD) there are evident divergences. According to the authors, the difference given by the decreasing of HDD in colder period and the increase of CDD in warmer periods of the most recent period of record is particularly striking.

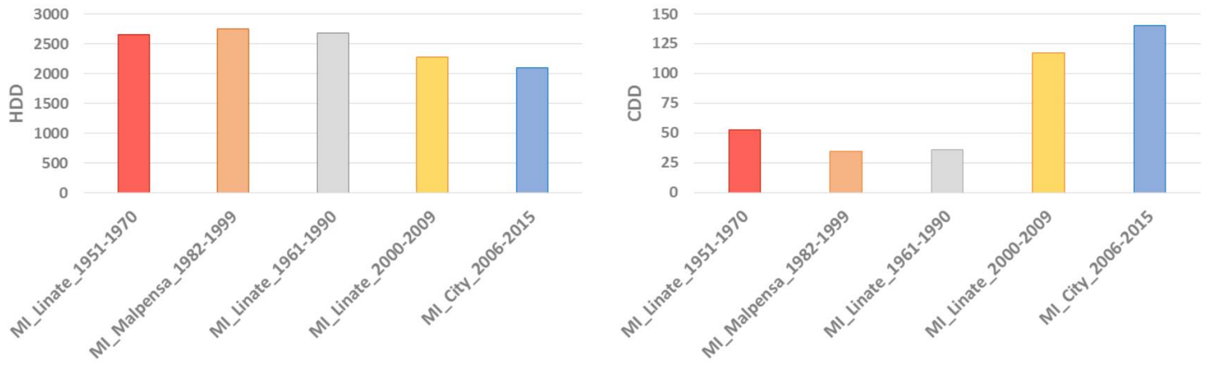

Figure 2: HDD and CDD distribution for the five different weather files (From Erba, et al., 2017)

Further comparisons have been performed taking in exam data from MI_Linate_1951-1970 and MI_City_2006-2015, representing respectively the coldest winter and the warmest summer. In this sense, the results regarding indoor comfort of a typical flat during summer condition are important. Besides the evident inequalities in energy needs evaluation for cooling and heating, different datasets impact basic decisions like the benefits of the external shading solution. In fact, based on the standard EN15251, *Table 5* illustrates the indoor thermal comfort of a living unit during cooling season, taking as reference both weather files. Particularly, there are reported the percentages indoor operative temperatures in and out the comfort zone (cat. I represent ideal adaptive condition), and the effects of including the shading device operation.

Table 5: Percentages of indoor thermal comfort (from Erba, et al., 2017)

	MI_Linate_1951-1970		MI_City_2006-2015		
	% in	% out	% in	% out	
cat I	74.6 %	25.4 %	19.3 %	80.7 %	including the shading device operation
cat II	97.0 %	3.0 %	65.3 %	34.7 %	
cat III	100 %	0.0 %	97.9 %	2.1 %	
cat I	60.0 %	40.0 %	10.7 %	89.3 %	without the shading device operation
cat II	86.9 %	13.1 %	13.5 %	86.5 %	
cat III	98.8 %	1.2 %	49.6 %	50.4 %	

It is the authors' opinion that if it was adopted old datasets (MI_Linate_1951-1970) the necessity of external solar shading may be underestimated compared to more recent data. Instead, including shading devices under newer datasets (MI_City_2006-2015) seems an ideal decision and a good cost-effective measure to passively improve the thermal comfort inside the building. Concluding, the authors indicate that recently recorded weather data may better represent current and future climate conditions given the inclusion of extreme weather events, and the general urgency of actualizing worldwide data according to them.

4. Discussion

4.1 Identifying the right climate scale

Comparing methods to investigate the climate with space-time scale confirms that ideal local knowledge is just partially achievable. This scenario is further complicated considering less accessibility of data outside developed countries and uncertainty of climate change effects. Referring to *Figure 2*, methods with long-period data recording reach city areas, but larger scales are normally more difficult to cover.

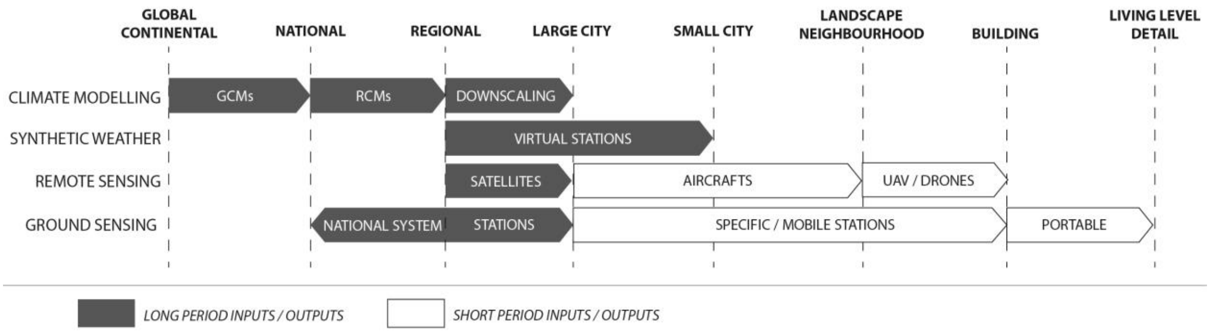

Figure 2: Current methods of climate data aggregation considering space-time scale

The reason is that spatial constraints influence climate information at different scale. Virtual weather stations may represent a solution to increase spatial definition reaching small city scale, but their data may be useless depending on site conditions. Furthermore, data from ‘physical’ stations, which are normally located outside city boundaries, may be capable of representing large areas, but they should be ‘urbanized’ for building projects (Mills et al., 2010).

In the meantime, time scale constraints also affect both ground and remote sensing. On the one hand, specific sensors or mobile stations yield relatively short time periods compared to other methods, being unable to illustrate typical climate behavior. On the other, while satellites can benefit of relatively long periods of data aggregation, data from aircrafts and drones are taken on demand. Additionally, time resolution of remote sensing is not capable of illustrating typical conditions, being adoptable only for real time or historical ‘snapshots’ of climate information. All these constraints affect reliability of climate data as happened to the case study illustrated above, highlighting the importance of further insights in the matter and the necessity of more case studies to uncover similar issues.

For building design, ‘linearity of interaction’ of climate scale indicates that local landscape features combined with building configuration are important. In this sense, improvements in climate observation may support local knowledge in the next future. For instance, sensors are increasingly affordable and located in strategic positions inside cities, going to replace mobile techniques that have poor recording times (Alcoforado, 2006). Additionally, virtuous examples like the Bullitt center in Seattle (recently awarded with the strict Living Building Certification) is mounting specific automatic stations to gather local climate data (Anderson, 2014). Having always more buildings that will ‘actively’ provide useful and long-term climate information will drastically reduce the distance between universal and local knowledge. In the meantime, remote sensing techniques are gradually spreading. For example, increasing use of sensors mounted on civil aircraft as illustrated in Norway (Stiberg, 2018), and a mayor adoption of drones by local institutions followed by betterments in sensor technologies, would implement space-time coverage and definition of multidimensional information.

In the next future, ethical and accessibility aspects will increase of importance. Although design teams that are unable to access typical information utilize short-term recordings, typical ones are generally more reliable. Actually, Climate Models are also improving quality and resolution of responses, but still half of global institutions restrict data access for research and commercial interests (Overpeck et al., 2011). Therefore, to technological advancements, better accessibility of information must be added.

Considering the above, the right climate scale should coincide with recent and long-term recordings together with landscape/neighborhood scale data, whose collection depends on technological improvements. Being aware of such features makes possible to apply the theoretical 'linearity of interaction' of climate scale within building design. Contemporarily, reaching different climatological scale, from micro to regional scale, is also important for decision-making (Chandler, 1976). Architects, analyzing more general scales, can manage lack of information, and among others, preserve habitats, predict future conditions, and consider climate change adaptation inside building design process.

5. Concluding comments

The paper has clarified space-time scale factors affecting quality of climate data collected for early design decisions. It has been illustrated importance of climate information inside low-energy building strategies, architect's activity for their adoption, and current technologies to gather climate data at different scale. In this sense, the investigation has showed that climate-informed design processes are not ideally supported mainly due to spatial and temporal scale constraints. Furthermore, time constraints issues have been illustrated by a case study in Milan. Concluding, the discussion suggests that although general climate scale is important, improvement and combination of different technologies and advances in data calculation will help reaching local scale. Additionally, better availability of information will increasingly support the introduction climate aspects inside building design process.

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Annex F – Paper III

バイオクライマティック建築理論の工業化建築への応用に関する研究

HOW THEORY OF BIOCLIMATIC ARCHITECTURE IS DEPLOYABLE TO INDUSTRIALIZED BUILDING?

○バルギーニ　ロレンツォ*、森下有**、野城智也***

Lorenzo BARGHINI, Yu MORISHITA, Tomonari YASHIRO

It is always more evident how the lack of integration of climatic aspects in architectural design has generated worrying environmental consequences at local and global level. The diffusion of identical prefabrication methods across different regions, and a scarce thermal capacity of buildings could be addressed as the main causes. To address these issues, most contemporary architects are proposing the bioclimatic method, with the intent of reconnecting architecture and climate to reduce consumptions and to foster regional differentiation. For this reason, this study wants to clarify whether bioclimatic architecture theory could support Industrialized Building (IB) realization to diminish its environmental impact.

Keywords: *bioclimatic architecture, Industrialized Building, architectural design, mass customization, quality, climate change.*
バイオクライマティック建築、工業化建築、建築デザイン、マス・カスタマイゼーション、品質、気候変動

Introduction

Cities are increasingly the centre of attention as the main accountable for the emission of GHG affecting climate change. The building sector alone are responsible for the 18,4% (IPCC synthesis report, 2014).

The prefabricated housing industry in Japan, which is a consolidated reality and a global reference point, has begun to take an interest in these issues and are implementing aspects related to sustainability in their production routines (Noguchi & Kim, 2010). In 2017 the 14.4% of the new houses built in the Japanese territory resulted being prefabricated (Japan Prefabricated Assotiation, n.d.) and Sekisui House alone has more than 2 million of prefab houses built to date (Sekisui House, 2017). Therefore, it is a phenomenon that should not be underestimated in view of mitigation and adaptation to climate change.

This study wants to compare the method applied by prefabrication companies towards climate change with bioclimatic theories adopted by an increasing number of architects to face the same issues. We want to emphasize whether there were similarities, and how this theory could support the Japanese prefabrication industry to face climate change in the next future.

1. The bioclimatic theory

Vitruvius argued in De Architectura that architectural forms were determined by geography and that differences between different forms were directly related to different characteristics of physical environments.

More recently in history, the relation between climatic and architectonical characters has been documented and catalogued by Jean Dollfus, a French geographer and traveller, who recognize analogies between climate and architectural configuration of the buildings visited during his travels (De Vecchi, 2012). In “Les aspects de l’architecture populaire dans le monde” (1954) the meticulous illustration and geographical collocation of various architectonical examples encountered by Dollfus suggest how in architecture geopolitical boundaries are much less decisive than climatic boundaries, which cross national territories.

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The relation between climate and architecture is further investigated in the 60s thanks to the contribution of the Hungarian architects Victor and Aladar Olgyay, both professors at the University of Princeton, who in those years have approached bioclimatic aspects to those related to architectural design (Barber, 2016). Victor Olgyay writes that the creation of balanced climatic conditions requires the deepening of fields of knowledge and that "one can readily identify two of these fields: climatology and architecture, which contain the beginning and end of the problem. By combining these two fields, considerations for building design can be deduced." (Olgyay & Olgyay, 1963)(see fig.1). In fact, according to the author, during the decision-making process, combining climatology and architecture it is possible to draw useful consideration for the following design phase.

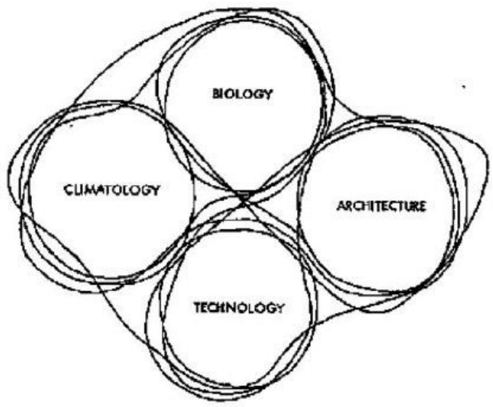

Fig. 1 Combining climatology and architecture. Source: Olgyay & Olgyay (1963) "*Design with Climate*"

Recently Ken Yeang has proposed a definition of bioclimatic design: "Generally, bioclimatic design is the passive low-energy design approach that makes use of the ambient energies of the climate of the locality to create conditions of comfort for the users of the building" (Yeang, 2015[1]) In addition to the relationship with the climate, it can be seen a strong relationship with the context, and how different climates lead to distinct architectural results. According to Yeang, it was precisely Victor Olgyay that influenced the regionalist theories of Kenneth Frampton, who became the dean of architecture in Princeton immediately after his death (Yeang, 2015). It is opportune to mention here that, at the time of writing the Olgyay's book *"Design with Climate: bioclimatic approach to architectural regionalism"* (1963) the current conception of climate change and the risks related to it were not yet widespread. The bioclimatic approach to architecture arises primarily as a reaction to the compositional uniformity given by the International Style on the one hand, and for more practical reasons such as that of responding to internal thermal comfort and cost reduction due to the use of mechanical air conditioning systems, to the other (Olgyay & Olgyay, 1963). Nevertheless, today we see a recovery of bioclimatic theories as a support for the reduction of carbon emissions and as a set of useful principles to be adopted before any other engineering system (Yeang, 2015). Putting things into practice, buildings must change their configuration like finishing, material masses, orientation, openings, volume and facade configurations to take advantage of climate constitutive elements (temperature, relative humidity, solar radiation, and wind).

Over time, other authors have contributed to the evolution of the bioclimatic theory like Baruch Givoni, Simos Yannas, Steven Szokolaj, Sergio Los, among others. In the case of Givoni, he reaffirms the first theorists' approach. Furthermore, in the book "Climate Considerations in Building and Urban Design" (1998) apart from combining the scientific approach with architectural aspects, he goes beyond indicating more general design strategies to follow in accordance with the climatic context of reference. Just as an example, regarding the zones with a hot humid climate and intense rains, Givoni suggests the designer some ideal strategies to minimize solar heating, to increase cooling during the evening and how to integrate external spaces as integral part of interior living spaces. In fact, he proposes a diffuse layout with the main spaces detached from the ground and protected by exterior vegetation, with ample openings to allow ventilation and thermal dispersion during night hours. For the author, it is important in such climates night and day ventilation management; acting on the orientation of main spaces considering prevailing winds and their disposition in the interior layout; the use of wide common spaces

[1] see preface at 2015 edition of Olgyay's book "Design with Climate"

or open spaces; the introduction of elements like verandas, pergolas or balconies in the case of tall buildings. On the other hand, his considerations change if the context is also characterized by cold winters. In such climate it would be better to have two different configurations: a more open one for the summer and a compact solution for the winter period. In most cases, for many reasons, it is not possible to reach the ideal configuration in practice. So, the ability of the designer resides in managing conflicting input to respond with the most appropriate configuration.

Nowadays many researchers and practitioners use the bioclimatic diagram proposed by Givoni or the ASHRAE comfort zone chart, both coming from the psychrometric diagram. In the Givoni' s one, around the ideal central zone there are 13 other zones individuating passive or active measures to be adopted in order to restore indoor thermal comfort (Manzano-Agugliaro, Montoya, Sabio-Ortega, & García-Cruz, 2015) (see fig.2).

In the last years, some authors have contributed to implement bioclimatic method and its application. For instance, it has been discussed the implication related to comfort of the interior temperature variation, through the use of additional diagrams or "comfort triangles" (Evans, 2008).

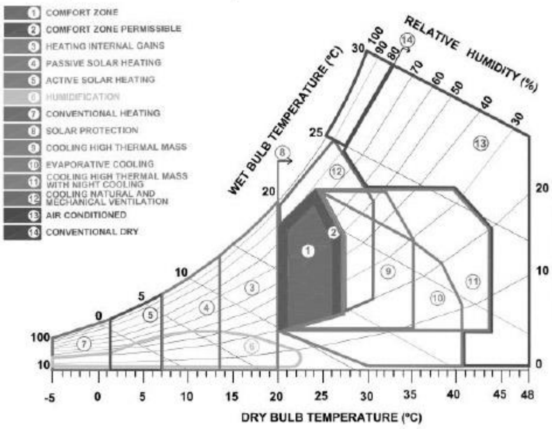

Fig. 2 Psychrometric chart adapted from Givoni[2]

There has also been discussed the main theory regarding adaptive mechanism of users (Yannas, 2011) and proposed how to redefine the concept of human comfort under people dynamic and constant change of behaviour, recognizing that "this changes the role of buildings in the process from that of providing comfort to that of providing the means for building inhabitants to achieve their comfort goal" (Nicol, 2011).

The theory in recent times seems to detach itself from the modernist rigidity of the first theorists, going towards an identification of adaptation strategies to accompany the aspects of mitigation derived from the past.

2. House prefabrication in Japan

Since its introduction in Japan in the 40s, the evolution of the industrialization of building has gone hand in hand with changes in the issues arising from the historical and economic context (Yashiro, 2014). Particularly, it is during the 70s that producers of prefabricated house gradually focused on quality and mid or high end products rather than quantity and affordable products (Noguchi, 2003), so much that today it seems Japanese companies are going in different direction compared for example to Europe (Linner & Bock, 2012) or Australia (Dave, Watson, & Prasad, 2017), where the main objective is always producing low-cost houses.

In order to respond to an increasingly widespread consumer dissatisfaction linked to the monotony and to the poor adaptability of prefabricated houses, the concept of mass-customization IB was introduced, which reached full maturity in the 90s (Yashiro, 2014). As a result, an economy of scale was maintained introducing qualities similar to the world of automation as high personalization, reliability, and the introduction of high-tech products along with proper design (Linner & Bock, 2012). Furthermore, there was a betterment of the productive process which permitted a drastic reduction of overproductions (being pulled by the consumer requests), and thanks also to the usage of steel-frame structures (adopted by the 80% of the companies) production scraps were reduced. Modularization and personalization was facilitated, altogether with the logic of just in time and just in sequence (Linner & Bock, 2012). In addition, the final product turned to be of high quality, antiseismic, durable and with various amenities which rise the quality of life of the occupants (Noguchi, 2003).

Shifting the attention to environmental

[2] Source: Manzano-Agugliaro, et al. (2015), *Review of bioclimatic architecture strategies for achieving thermal comfort*

qualities, Sekisui House, one of the largest producer in Japan, in 2005 declared its environmental vision as an objective for the following years. In 2006, it indicates guidelines addressing management of energy, resources, chemical substances, and respect for the ecosystem. Subsequently, in 2008 he declared the objectives for 2050, such as eliminating carbon emissions from the entire production cycle and promoting of the Green First ZERO housing (Net-Zero-Energy Houses), an improved version of the Green First homes launched in 2009 (see Fig. 3). Regarding comfort, the company introduced highly insulated casings, and starting from 2016, began to introduce multi-layered vacuum-glazed glass to increase the insulating capacity and consequently to decrease the dispersion of energy (Sekisui House, 2017).

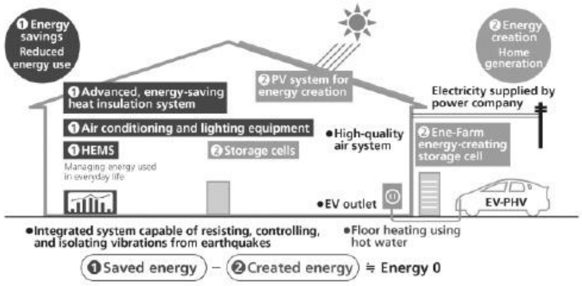

Fig. 3 Green First ZERO Model, Sekisui House[3]

Moreover, thanks to the cost-performance based marketing strategy and the possibility of lowering the production costs of plants such as photovoltaics and fuel cells, the diffusion of such technologies has seen an increase despite the decline in the housing market of the last period. (Noguchi & Kim, 2010)

Similarly, another large company like Misawa Homes combines strategies for hyper-insulation and airtightness but go further adding climate considerations. The so-called "micro-climate design" of Misawa Homes considers basic passive strategies related to local climate, wind passage patterns, available sunlight, landscape, surrounding trees, and the location of neighboring houses. First, they propose north-south orientation (based on local factors) to improve natural ventilation and the provision of openings, ceiling fans, top-lights and transoms to facilitate the release of hot air inside. Second, they consider the construction of overhangs to shade the house from direct sun combined with the introduction of balconies, and the management of external vegetation to manage shadows according to the season. Third, there is the option to introduce heat gain concrete floors which release heat at night (Misawa Homes, n.d.).

Recent tendencies of some of the major prefabrication companies are focusing on management of domestic housing services during the lease or rental period (Yashiro, 2014; Linner & Bock, 2012). These services, initially aligned to the Infill System concept and nowadays to that of SMART houses, also consider aspects related to energy management. For instance, Misawa Homes has introduced in its flagship model, an ITC-based Home Energy Management System (HEMS), and a charging system for electric cars (Misawa Homes, n.d.). Sekisui Heim, another company subordinated to Sekisui chemical, is instead implementing an interactive monitoring and benchmarking system with the possibility for inhabitants to modify the performance of the dwelling during the operational phase of the building (Sekisui Heim, 2017). The interest in such services leads these companies to extend their market to the life phase of buildings and thus becoming service providers instead of merely product producers (Yashiro, 2014).

3. Discussion

The implementation of environmental qualities of Japanese prefabrication companies offers numerous elements of discussion. Although both bioclimatic theory and manufacturers' approach introduced so far come from different basis, it is possible to find some aspects in common that could create some synergy to face climate change. In fact, bioclimatic theory could be defined belonging to the sphere of the "eco-cultural" logic, in which dwelling passes through "a building that is adapted to local, bioregional and cultural characteristics" (Guy & Farmer, 2001). At the same time, the environmental vision of the prefabrication companies interprets sustainability according to an "eco-technic" logic, based on technical and scientific progress and considering global environmental issues from a distance (Guy & Farmer, 2001). But apart from these conceptual divergences,

[3] Source: Sekisui House (2017), *Sustainability Report 2017*

overt time, both methods are returning to converge thanks also to the adoption of mass-customization process.

First, Sekisui House is softening the globalizing trends that characterizes prefabrication in general. They are considering regional and climatic variations to meet customers' expectations through the creation of regionally based model parks (Linner & Bock, 2012). From the perspective of bioclimatic theory, this aspect of customization, alongside aesthetic factors, have important implications for mitigation of climate change. In fact, the uniformity of prefabrication or identical technological solutions it is proven to be incompatible with the climatic variety of the various contexts, as various publications indicates in the case of Morelia, Mexico (Becerra-Santacruz & Lawrence, 2016), Sana'a in Yemen (Al-Sallal, 2001), and Cuba (D' Ettorre, 2016), among others. Therefore, according to bioclimatic theory climatic aspects must be addressed starting to local climate interpretation. The great climatic variety of the Japanese territory (divided into 6 distinct climates) would result in at least 6 distinct architectural configurations (without considering topographic variations and other implications due to the location) which would multiply considering 4 different seasons and at least 2 configurations between day and night. In this sense the bioclimatic theory would seems to give support in deepening and giving greater value to a "climatic regional customization". As suggested by Auer, Vanwyck and Olsen "when you consider different traditional houses in Boston are from those built in New Mexico, it seems ludicrous that we now aim to design buildings in the same way for both climates" (Auer, Vanwyck, & Olsen, 2012).

Second, in the case of Misawa Homes, there is a tendency to integrate passive solutions in the design process (Misawa Homes, n.d.), in line with the bioclimatic theory. As a matter of fact, where there are no economic possibilities, or the consumer does not give sufficient value in investing in advanced energy generation systems, not only comfort decreases but consumption and emissions increase due to the use of active systems that correct basic design errors. This benefits consumer's economy but undermines the objectives set by the company itself and society in general in reducing emissions. However, it should be verified with further research that the adoption of active strategies takes place only in support of an architecture already passively optimized. In fact, "passive ways are however preferred because of their low cost and good energy performance. Therefore, the appropriate strategy is to compensate for their insufficiencies with active systems, which will be smaller and cheaper "(Roulet, 2018). This leads often to make the design more complex and difficult to manage, but in favor of better cost-effectiveness and equity, considering that hi-tech active systems are generally more prone to malfunctions and more fragile. In addition, it would contribute to increase comfort adaptability of users and physical multiplicity of buildings in favor of climate change adaptation. For this last aspect, it is worth mentioning the case of the award-winning LILAC community in Leeds, UK. It has been shown how the physical redundancy given by the design of architecture (infrastructural), accompanied by social redundancy (the community of residents), has allowed the creation of a community potentially able to respond to the uncertainties of climate change (Stevenson, Baborska-Narozny, & Chatterton, 2016). For example, the adoption of multiple orientation and different kind of openings for windows permitted to meet users behaviour and at the same time to respond to climate change adaptation.

Third, the prefabricated companies analyzed in this study are unanimous in adopting the hyper-insulation of the envelope. It is considered an excellent solution to reduce the dispersion of thermal energy and reduce consumption, but its adoption must be evaluated based on local climatic characteristics. Often hyper-insulation and airtightness leads to undesirable effects in warmer months, as has been confirmed recently by analyzing the comfort of ecological highly insulated houses in Denmark. It has been found that they meet comfort during winter periods, yet they have problems of overheating in summer, which could be exacerbated by the future global warming (Marsh, 2016). Therefore, adopting global solutions to improve comfort can sometimes be counterproductive because it may be incapable of responding to the complexity of the climatic context. The bioclimatic theory could prevent these problems adopting climate analysis before the design process and suggesting how to act depending on climatic variations.

4. Conclusion

This study suggested how the recent environmental approach of prefabrication companies can be integrated with theories coming from the bioclimatic method.

The great opportunity represented by mass-customization in introducing high-tech solutions and services by lowering production costs could be integrated with a improved response to climate constraints at the local level. At the same time, it would produce an architecture in which basic passive solutions support energy production systems, increasing efficiency, resilience and adaptation. Furthermore, there would be greater awareness in choosing the most suitable design strategies for the geographical refence context.

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