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Use of Automated Control Systems and Advanced Energy Simulations in the Design of Climate Responsive Educational Building for Mediterranean Area

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Abstract: Over the decades, a rapidly changing climate has prompted the world's most influential leaders and institutions to take action against such an imminent threat. The introduction of Nearly Zero Energy Building (nZEB) concept, though, has barely triggered a major shift, while voluntary labelling systems do not seem to offer any reasonable alternative. Building design ought to be readdressed from the ground up, with climate-responsive constructions servings as a valuable starting point for the purpose. In this paper, conventional bioclimatic design is enhanced and supported by the introduction of Building Automation Control Systems: Typically, the former determines long-term seasonal patterns, whereas the latter only affects the short-term behavior. Their schedules are based on realistic assumptions, while set-points are fine-tuned following energy simulations. Good results have been achieved for a case-study facility in Porto, both in terms of indoor adaptive thermal comfort (the simulated operative temperature complies the adaptive comfort model for more than 98% of the reference year) and energy use (reduced by 53%, compared to a baseline building, devoid of any automation system). Being focused on the decision-making rather than on specific items of design, the authors claim that such an approach may be employed in any climate, regardless of the building type or size, as long as the process is driven by a genuine analysis of the local context (i.e., climate) and by purposefully devised energy simulations.

Keywords: climate responsive building; advanced energy simulation; automated control systems; building automation; Mediterranean climate

1. Introduction

Energy efficiency is today no longer just a question of money, but instead a way to reduce the emissions of greenhouse-gases, commonly held to be responsible for global warming [1]. According to the statistics, buildings account for about 25%, 23%, and 26% of, respectively, Europe's, Portugal's, and Italy's primary energy use [2], and although the housing sector should be blamed for that, it is up to the public realm to set a good example.

As per the plan "202020", introduced by the 2009/29/CE Directive [3], primary energy use and CO2 emissions shall be reduced by 20% within 2020. To this end, the 2010/31/EU Directive [4], the recast of the original EPBD, introduced the so-called Nearly Zero Energy Building ("nZEB") concept; unlike Zero Energy Buildings ("ZEBs") and Plus Energy Buildings ("PEBs"), nZEBs are grid-connected, "high performance buildings, whose low amount of required energy is extensively supplied by renewable energy sources" [5]. Newly designed public buildings must be nZEBs starting from 01/01/2019, while private developments from 01/01/2021 onwards only.

In spite of this, the nZEB is more of a regulatory concept; it was up to each country to come up with a suitable definition [5,6], which has normally been encompassed within the national energy labelling framework [7]. In Italy, according to the Law n°90/2013 and its Implementing Decrees (Date of issue: 26th of June 2015), a nZEB must comply with very high requirements (as far as envelope and HVAC systems are concerned) and cover at least 50% of its energy and DHW demand with on-site renewable energy sources. The Laws n°118/2013 and n°250/2015 make similar provisions in Portugal. It is no operative tool and it cannot yield, therefore, any qualitative guideline. Voluntary rating systems [8], such as PassivHaus [9–15] and LEED [16], were introduced long before the nZEB, in 1988 and 1998, respectively. The latter is based on credits; it was conceived in the USA, but has eventually caught on in Europe. The former, which unlike LEED, is based on performance evaluation, was developed in Central Europe and later adapted to other climate zones, either colder or warmer, thanks to institutional efforts (EU's C.E.P.H.E.U.S. project, [17]) as well. Nonetheless, climate change and heat waves, which occur nowadays at an alarming rate [18] and whose effects we are now beginning to experience, force us to reconsider the way buildings are designed. Otherwise, they are inevitably going to suffer from overheating, and require larger HVAC systems to compensate for higher cooling loads even in traditionally cold climates, as anticipated in several studies [10–12,19,20]. Unfortunately, both labelling and regulatory systems belong in the last steps of the design-process, and have no influence whatsoever on the preliminary stages, when the most influential decisions are made; designers should therefore reject an assessment-oriented attitude in order to embrace a more holistic approach to design, both on the building [21] and on the urban [22] scale. Bioclimatic design [23] should be the stone upon which to build a more systematic approach to design. Although frequently confused with sheer environmental design, it is a century-old discipline, which prefers the context over the concept; bioclimatic constructions are carefully crafted on a case-by-case basis following a well-defined hierarchy, taking advantage of their immediate surroundings in order to reduce their environmental footprint.

Several studies have been concerned about this topic: Soutullo et al. [19] compared conventional and bioclimatic buildings, Rodriguez-Ubinas et al. [20] concentrated on the prototypes from Solar Decathlon Europe 2012, while Tzikopoulos et al. [24], found correlations among the energy indicators of 77 bioclimatic buildings.

In the past decades, the topic of climate-based design for buildings has been widely studied and discussed, up to the importance of having buildings resilient to climatic conditions. Despite this attention, the sheer volume of studies and also the many different directives and national laws issued nationally in the Mediterranean countries have not succeeded in creating clear, shared, and generalizable methodological approaches, useful for guiding the design stage of architects and building engineers.

With this contribution, the Authors wish to show how is possible to obtain remarkable energy performance for Mediterranean buildings, both in winter and summer season, combining traditional construction techniques with automatic regulation and control systems. In particular, this goal is obtained basing the design choices on the possibility of modifying some properties of the building envelope (appropriately managed by building automation control systems) and of bringing accurate dynamic energy simulations into the design process. This approach is applied to a real case study, which is not by chance, a partially underground academic facility in Porto (Portugal), whose only exposed facade—the Southern elevation—acts as the main control device. The building employs some passive solar design features, among which is a considerable amount of thermal mass, which well-justifies a dynamic analysis of heat exchange phenomena.

2. Materials and Methods

2.1. Case-Study Location

The Porto School of Architecture (or FAUP: Faculdade de Arquitectura da Universidade do Porto) is located on the Campo Alegre University Campus and was designed during the second half of the 1980's by Álvaro Siza Vieira [25]. It consists of four towers of classrooms facing South and a long shallow block to the North, which houses the offices, the library and the auditorium; the two are connected on the ground floor by a slab containing technical rooms. In the last decades, the faculty has grown exponentially; a new canteen had become indispensable, while the surrounding areas must be freed from invasive parking spaces. An extension, designed of as an independent new wing (along with the design process) will provide enough space for a new catering service as well as a larger study room.

The climate variables, for the case-study location, were analyzed and averaged over each month (Table 1); on this basis, the Köppen label [26] was determined together with the number of heating and cooling degree-days (Table 2).

Table 1. Climate data: Monthly means of climate variables.

Month	$T_{AIR,MM}$	$T_{A,MIN,MM}$	$T_{A,MAX,MM}$	$T_{GRO,MM}$	$I_{H,HM}$	RH_{MM}	$V_{WIND,MM}$	$D_{WIND,MM}$
	°C	°C	°C	°C	Wh/m^2	%	m/s	$^{\circ}{}_{NORTH,CW}$
January	9	0	17	12	187	80	2	100
February	11	2	21	11	253	81	4	172
March	12	1	21	11	346	78	3	185
April	13	5	26	12	425	76	3	194
May	15	3	24	14	443	78	4	227
June	18	9	29	15	474	75	1	231
July	19	10	32	17	457	80	3	229
August	19	10	31	18	450	76	2	163
September	18	9	30	18	374	81	1	202
October	16	6	27	17	293	76	3	168
November	12	1	20	15	181	80	3	157
December	10	0	19	13	164	82	1	162

Note—$T_{AIR,MM}$, $T_{A,MIN,MM}$ and $T_{A,MAX,MM}$ are, respectively, the monthly mean air temperature and its recorded minimums and maximums, $T_{GRO,MM}$ is the monthly mean ground temperature, $I_{H,HM}$ is the monthly mean global solar radiation, RH_{MM} is the monthly mean relative humidity, $V_{WIND,MM}$ is the monthly mean wind speed and $D_{WIND,MM}$ is the monthly prevailing wind direction (measured clock-wise in degrees North).

Table 2. Climate data: Characterization of the climate type.

Location	Köppen	HDD	CDD
Porto (Airport) 41.23° N, 8.68° W	Csb	1566 (T_{REF} = 20 °C)	11 (T_{REF} = 26 °C)

Note: "Csb" indicates a less common form of Mediterranean climate. "C": mean temperature of the coldest month above −3 °C; "s"; rainfall during winter is at least three times in summer; "b"; mean temperature of the hottest month is below 22 °C. HDD and CDD are heating and cooling degree days, calculated based on T_{REF}, according to the ISO EN 15927-6/2007 regulation (Hygrothermal performance of buildings—Calculation and presentation of climatic data—Part 6: Accumulated temperature differences. Degree Days).

Results were obtained from the WEC v1.0 dataset of the American Society of Heating and Air Conditioning Engineers (ASHRAE), relating to the Pedras Rubras weather station (Porto's Francisco Sà Carneiro Airport) and artificially made up of data collected between 1982 and 1999 [27]. Porto presents windy, heating-dominated climate, an assumption confirmed by its "Csb" classification; this ensues from its proximity to the Atlantic Ocean, whose large thermal mass mitigates both heat and peak waves, keeping temperatures quite low in the summertime.

2.2. Design Approach

The design approach of a climate responsive building aims at shifting the attention from late assessment procedures to the earliest stages of the process, when each choice has a great influence on the outcomes, both in terms of quality and costs. As information about the surrounding context is processed from the beginning, the building can be designed to exploit the climate conditions in its favor, in order to reduce its energy use. The design of a climatic responsive building steps beyond regulations, concepts and ratings systems, to look at the bigger picture, and to unveil site-specific synergies that would otherwise pass-by unnoticed [28]. An intuitive hierarchy guides the whole process, prioritizing passive over active design; this choice can generally save some of the costly and exasperated equipment that is sometimes needed in poorly designed buildings. Taking cue from past experience and previous case-studies, as well as from guidelines and rules of thumb [23,29], these strategies have been translated into a technically feasible solution. The background of each strategy and its influence on present-day rating systems and regulations are discussed in the following subsections.

2.2.1. Orientation

In temperate climates, buildings have always been shaped as elongated South-facing blocks, which guaranteed maximum and minimum gains in winter and summer, respectively (Figure 1). Modern studies [30,31] confirmed that an East/West elongation is an optimal compromise; in particular, those who focused on Compactness [32] or South Shape Factor [33] have observed that the energy use increases with the East and West façade areas. Ourghi et al. [34] found further correlations amongst glazing type, glazing area, and energy use. In this case-study, the building replaces the former parking lot, whose shape is conveniently long and narrow (the ratio between sides is above 9) is and slightly tilted (12°) from the East/West axis (Further data can be found in Table 6). As a comparison, LEED credits are awarded to buildings whose long sides are at least 1.5 times the short ones, and whose long axis are tilted less than 15° from the East/West axis. The shape and orientation of the building are generally site-specific, as hot and cold climates require both compact volumes with few openings, while humid areas call for long and permeable structures.

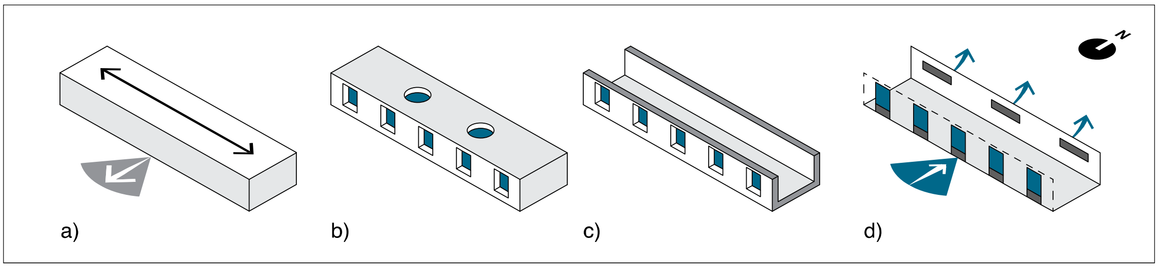

Figure 1. Bioclimatic strategies—(**a**) Orientation/form finding, (**b**) daylighting, (**c**) passive solar design and thermal mass, and (**d**) natural ventilation.

2.2.2. Daylighting

Especially in public buildings, lighting is often what contributes most to the energy use [35–39]. It is therefore preferable to exploit daylight (Figure 1b), which is loosely site-specific, as sky conditions depend on latitude, while the Sky View Factor varies from site to site according to surrounding buildings and topography. Side-lighting is a common solution, but unless patios and courtyards are used, room depth should be limited to 2.5 times its height, as suggested in the EN 15193-1/2017 (Energy performance of buildings—Energy requirements for lighting—Part 1: Specifications). Top light (roof monitors, clerestories, skylights, or solar tubes) is usually uniform and glare-free, but only suitable for large open spaces on the top floors. In the case-study building, South-facing side windows, sized to 20% of the floor surface, provide a connection to the outside, yet blocking direct light during summer. Translucent skylights, on the other hand, release an evenly distributed and glare-free top-light into the building. While innovative concepts based on advanced daylight simulation based on climate based daylighting modelling, such as Spatial Daylight Autonomy and Annual Sunlight Exposure (ASE) are frequently used in advanced daylight simulation [40–43] and they have also been recently adopted by LEED; the Daylight Factor was taken in this case as the reference metric; benchmarks are shown in Table 3, while actual calculated values can be found in Table 6.

Table 3. Building design: Thermal zones.

ID		S	V	Occupants	Weekday	Weekend	ACH	E_M	DF
		m^2	m^3	n°	h	h	Vol/h	lx	%
A1	Study room	370	1590	110	08–24	08–18	3.0	500	3
A2	Hallway	56	148	5	08–24	08–18	1.5	200	1
A3	Common room	56	148	10	08–24	08–18	3.0	200	1
A4	Corridor	166	510	5	08–24	08–18	0.5	100	1
B1	Canteen	521	1820	240	10–16	Closed	6.0	300	2
Total		1170	4216	400					

Note—S is the surface. V is the Volume. ACH is the air change rate, whose minimum target value is determined according to the EN 13779/2007. E_M is the maintained average illuminance, whose minimum target value is determined according to the EN 12464-1/2011. DF is the daylight factor, whose minimum target value is determined according to the UNI 10840/2007.

2.2.3. Insulation/Glazing

Thermal insulation controls both heat transfer and water vapor diffusion through the envelope. Current regulations, revised in the wake of the EPBD, do not specify insulation requirements, but rather limits (based on the climate zone) the surface mass, to the local and global (wall and building levels) thermal transmittance and (limited to glazing) to solar factor. Reference values can be found for both walls and glazing in Table 5. In rating systems such as PassivHaus, although thick insulation and triple glazing have always been considered as fundamental, requirements that are indirectly expressed in the form of energy loads and demand thresholds.

2.2.4. Passive Solar Design

The Sun is the oldest and most efficient heating system known to man. While solar design can be applied everywhere, it must be regarded as site-specific: Hot regions, arid or humid, needs no heat, while in cold areas, the required amount of radiation is proportional to the outdoor mean temperature of the cold season. There are different ways in which passive solar gain (Figure 1c) can occur, among which direct gain, as opposed to indirect gain, is the simplest; in any case, however, measures must be taken against glare and overheating. In a PassivHaus, South windows should be large and present a high solar factor, balanced out by a very low thermal transmittance. LEED, on the contrary, assigns credits if the surface of South windows is carefully shaded in summer, and at least 50% larger than the sum of East and West window surfaces. In the case-study building, glazing is located on the roof and to the South only; skylights have a highly reflective external surface, while windows, sized to 20% of the floor surface (matching the need for daylighting as well) and conveniently set back from the façade, block direct sun during the hottest periods of the year. Additional data, such as Window-to-Wall ratios and Glazing ratios, can be found in Table 6.

2.2.5. Thermal Inertia

The benefits of thermal inertia (or thermal mass) have been studied extensively, often in connection with layering [44]. It is not a coincidence that architecture has been, for the most part, "heavyweight" [37] in the past; nowadays, superlight glazed envelopes and curtain walls are catching on dramatically, and will eventually cause the increase, even in temperate climates, of heating and cooling loads. Adequate mass has beneficial effects in many climates, except for humid regions; in cold areas, it collects excess heat during the day and returns it back at night-time, while in hot-arid regions, it shifts the peak waves towards the evening; even so, neither LEED nor PassivHaus make any provision in this direction. Some requirements set by the Italian legislation can be found in Table 5. Literature [29] suggests massive surfaces, less than 10 cm thick and large up to nine times the floor area. If thermal mass is part of the outer envelope, correct layering is also important [44–48]. If the system operates intermittently, insulation must be placed on the inside (heating dominated climates) or the outside (cooling dominated climates). For a continuously operating system, insulation should be external, and the mass should be at least 25 cm thick [49]. In the case-study building, both structural concrete walls (26 cm thick) and exposed concrete floor slabs (10 cm thick) act as thermal mass, with the overall storage surface adding up to more than 1700 m^2.

2.2.6. Natural Ventilation

Vernacular architecture has always counted on natural ventilation (Figure 1d), despite its scarce dependability, as mechanical air change was not yet possible; primitive examples of evaporative cooling or underfloor heating were already being used centuries ago. The correct approach depends on the location, while in colder climates, mechanical ventilation and heat recovery are employed out of necessity, in temperate regions most houses are in fact free-running [50], although the results of some studies have supported the use of natural ventilation in office buildings [51,52]. It is therefore not surprising that PassivHaus leaves no room for natural ventilation, while LEED refers to either ASHRAE Standard 62-1/2010 (Ventilation for Acceptable Indoor Air Quality) or other equivalent local regulations. In Europe, the EN 13779/2007 (Ventilation for non-residential building—performance requirements for ventilation and room-conditioning systems) requires, for an "IDA 2" class (New buildings), an air change rate of at least 12.5 L/s per person. The required air change rates, expressed in terms of volumes per hours, can be found in Table 3, while actual air renewals, determined using energy simulation, are discussed in the following section (Section 4.6, Figure 13) There are very few guidelines for natural ventilation, proper orientation (within 45° of prevailing winds), vent size (outlets should be larger than inlets, placed on opposite sides and at different heights; actual values can be found in Table 6) and space arrangement (the airflow should be unobstructed).

In Porto, strong winds come mainly from the South and North-West, while cold winds blow from East; the vents were therefore placed on the South façade and on the roof (facing North), in order to trigger both cross and stack ventilation.

2.2.7. Building Automation Contribution

Building Automation Control Systems (BACS), in the form of sensors and actuators, have long since become cheap and user-friendly devices, as well as an essential feature of any modern energy-efficient building. Their contribution is strictly affected, however, by the occupants' behavior [53,54], which may easily deviate from the optimal (users tend to override automated devices). In fact, although seemingly illogical, a Danish study [55] reported that more than 60% of people still prefer, on average, manual controls for lighting, ventilation, and solar shading. Other studies [56,57] have detected the perception of loss of control amongst those occupants, whose workplaces were fitted with automated shading devices, blinds, and light controls. BACS are contemplated by LEED in so far as they help meet other requirements, such as reduced energy use and light pollution through scheduling and occupation control or real-time monitoring and metering. In this case-study, BACS have been embedded into all those components, whose behavior directly influences one or more of the aforementioned strategies (see the Hierarchy in Section 2.3): automated solar shading (Passive solar design and Daylighting) automated operable vents (Natural ventilation) and automated light controls (Daylighting and Energy efficiency). Control strategies and set-points are optimized and further discussed within Section 3 in light of energy simulation.

2.3. Technical Solutions Chosen for the Case Study

Based on the guidelines contained in the previous subsections, a design proposal was outlined (Figure 2). The result is a partially underground construction, located South of the School's premises, in place of the existing outdoor parking lot. The building's only exposed façade overlooks the river *Douro* and conceals a canteen, a study room, and an underground parking space. Passive design maximizes solar gains, while the underground volume minimizes losses, thus taking advantage of internal gains and protecting the envelope against the rainy and windy weather. Different kinds of opening, including skylights and domes, provide the indoor space with plenty of daylight, while carefully placed vents help reduce overheating, triggering both cross and stack ventilation. Only a portion of the whole building, highlighted in red in the floor plan in Figure 2, was further analyzed from the energy point of view (see Section 3). Figure 3 visualizes thermal zones and envelope assemblies; the latter are fully characterized in Tables 3–5, and are not further optimized. Table 6 summarizes reference values and data for both the opaque and the glazed envelope, and as usual [12,20,21], surface ratios and indexes were used to characterize the building layout and geometry.

In order to enhance the behavior of this reference building a series of advanced energy simulations were carried out using EnergyPlus™ simulation software. In detail, with the results of the simulations, BACS schedules and set-points can be tuned and optimized, to achieve satisfactory indoor comfort conditions and a reduced energy use. A conventional energy analysis would be impossible to carry out; the effects of thick insulation and thermal mass can only be appreciated on a long-term basis, whereas internal and solar gains have an almost immediate influence on the energy demand-response balance. As in other case-studies [11,12,18,19,21,28], energy simulation has been extensively employed all throughout the process; simulations provided a first feedback, on which basis further control strategies and schemes were devised. As most design strategies must be regarded as site-specific, there are neither invariable criteria, nor representative indicators to be given. However, even though this study concentrated on a single case-study, an educational facility, the process can be seamlessly adapted to other climates and applied to buildings of different sizes and types.

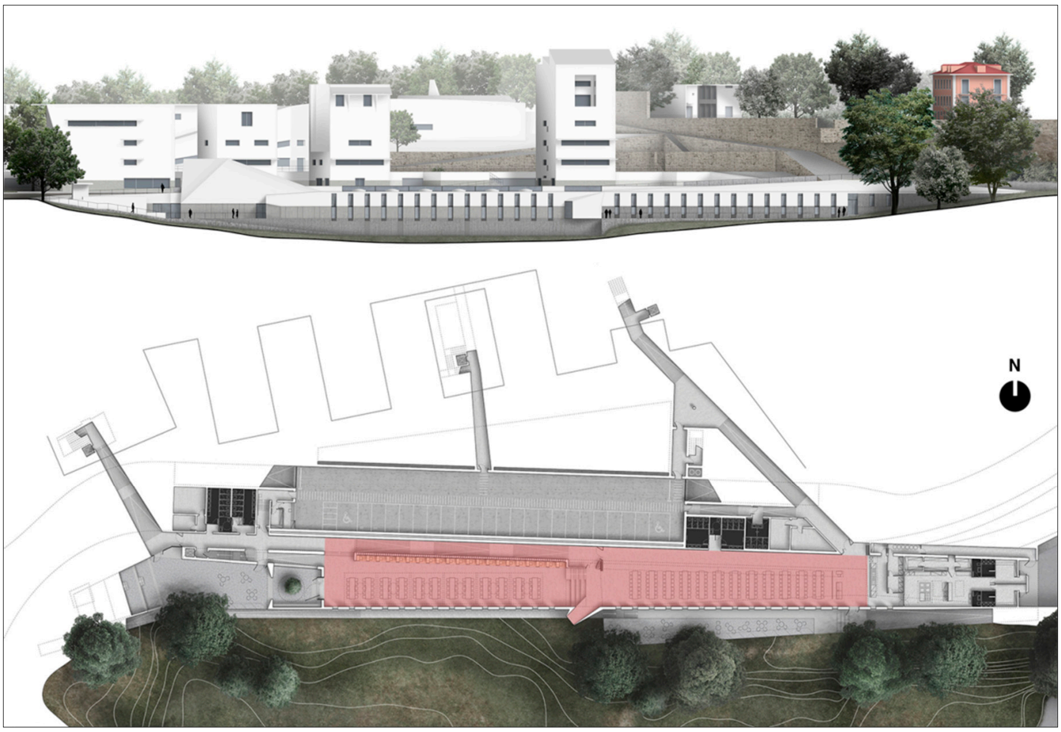

Figure 2. Building design: Main elevation and floor plan.

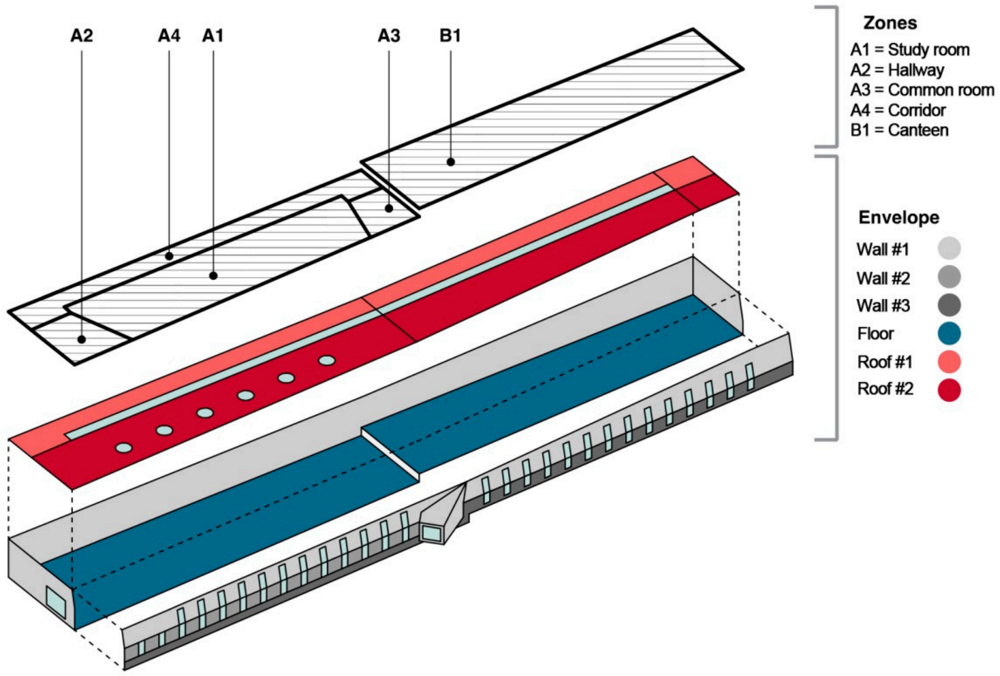

Figure 3. Building design: Thermal zones and envelope types.

Table 4. Envelope design: Layers.

Wall #1	Plaster (2 cm), Concrete (26 cm), Membrane + EPS (15 cm), Thermal-insulating Plaster (2 cm).
Wall #2	Plaster (2 cm), Concrete (26 cm), Membrane + EPS (20 cm), Granite Slab (4 cm).
Wall #3	Plaster (2 cm), Concrete (26 cm), Membrane + EPS (12 cm), Fair-faced Concrete Slab (12 cm).
Floor	Concrete Slab (25 cm), EPS (15 cm), Fair-faced Concrete Finishing (10 cm).
Roof #1	Concrete on Corrugated Steel (8 cm), Membrane + EPS (14 cm), Granite Blocks on Sand (15 cm).
Roof #2	Concrete on Corrugated Steel (8 cm), Membrane + EPS (14 cm), Green Roof (20 cm).
Glazing	Low-e + Solar control Triple glazing (4-15-6, 8-15-4 mm; Argon-filled Air gaps).
Domes	Heat-stop external layer, Transparent middle layer, Translucent internal layer.

Table 5. Envelope design: Properties.

	U	**U_{LIM}**	**g**	**g_{LIM}**	**Y_{IE}**	**$Y_{IE,LIM}$**	**σ**	**σ LIM**	**τ**	**f**
	W/m²K	**W/m²K**			**W/m²K**	**W/m²K**	**kg/m²**	**kg/m²**	**h**	**-**
Wall #1	0.16	0.30	-	-	0.016	0.10	671.00	230	11.03	0.099
Wall #2	0.18	0.30			0.018		771.40		11.31	0.097
Wall #3	0.25	0.30			0.024		759.60		11.50	0.092
Floor	0.22	0.25			/		337.50		/	/
Roof #1	0.18	0.25			/		522.50		/	/
Roof #2	0.21	0.25			/		823.00		/	/
Glazing	0.50	2.20	0.37	0.60	-					
Domes	1.90	2.20	0.31	0.60	-					

Note—U_{LIM} includes the effects of thermal bridges on the opaque envelope. U is the Stationary Thermal Transmittance. g is the Solar Factor. YIE is the Dynamic Thermal Transmittance. σ is the Surface Mass. τ is the Time Shift and f is the Attenuation Factor.

Table 6. Building design: Reference values and data.

Building Data				Vents area (Inlets)	$A_{V,IN}$	m^2	12
Gross floor area	$A_{FLOOR,TOT}$	m^2	4200	Vents area (Outlets)	$A_{V,OUT}$	m^2	16
Analyzed floor area	A_{FLOOR}	m^2	1170	Vents area ratio	$A_{V,IN}/A_{V,OUT}$	-	0.75
Analyzed volume	V	m^3	4700	**Opaque Envelope**			
External Surf. (total)	$A_{EXT,TOT}$	m^2	3400	Compactness (total)	$A_{EXT,TOT}/V$	-	0.72
External Surf. (air)	$A_{EXT,AIR}$	m^2	1700	Compactness (air)	$A_{EXT,AIR}/V$	-	0.36
South	$A_{EXT,S}$	m^2	538	Compactness (ground)	$A_{EXT,GRO}/V$	-	0.36
Roof	$A_{EXT,R}$	m^2	1105	*Directional Shape Factor*			
West	$A_{EXT,W}$	m^2	57	North	$A_{EXT,N}/A_{EXT,TOT}$	-	0.14
External Surf. (ground)	$A_{EXT,GRO}$	m^2	1700	South	$A_{EXT,S}/A_{EXT,TOT}$	-	0.16
North	$A_{EXT,N}$	m^2	462	Roof	$A_{EXT,R}/A_{EXT,TOT}$	-	0.32
East	$A_{EXT,E}$	m^2	68	Floor	$A_{EXT,F}/A_{EXT,TOT}$	-	0.34
Floor	$A_{EXT,F}$	m^2	1170	West	$A_{EXT,W}/A_{EXT,TOT}$	-	0.02
Ext. Ratio (air/ground)	A_{RAT}	-	0.50	East	$A_{EXT,E}/A_{EXT,TOT}$	-	0.02
Glazing Surface	$A_{GL,TOT}$	m^2	230	**Glazed Envelope**			
North	$A_{GL,N}$	m^2	0	Window/Wall ratio	$A_{GL,TOT}/A_{EXT,TOT}$	-	0.07
South	$A_{GL,S}$	m^2	95	Window/Ext. S. ratio	$A_{GL,TOT}/A_{EXT,AIR}$	-	0.13
Roof	$A_{GL,R}$	m^2	120	Window/Floor ratio	$A_{GL,TOT}/A_{FLOOR}$	-	0.19
West	$A_{GL,W}$	m^2	15	*Directional WWR*			
East	$A_{GL,E}$	m^2	0	North	$A_{GL,N}/A_{EXT,N}$	-	0.14
Length (approx.)	L	m	111	South	$A_{GL,S}/A_{EXT,S}$	-	0.17
Depth (approx.)	D	m	12	Roof	$A_{GL,R}/A_{EXT,R}$	-	0.11
Building Ratio	L/D	-	9.25	West	$A_{GL,W}/A_{EXT,W}$	-	0.26
Thermal Mass	A_{MASS}	m^2	1782	East	$A_{GL,E}/A_{EXT,E}$	-	0.02
Daylight Factor				*Glazing ratio*			
A1	DF_{A1}	%	4.10	North	$A_{GL,N}/A_{GL,TOT}$	-	0.00
A2	DF_{A2}	%	1.75	South	$A_{GL,S}/A_{GL,TOT}$	-	0.41
A3	DF_{A3}	%	1.90	Roof	$A_{GL,R}/A_{GL,TOT}$	-	0.52
A4	DF_{A4}	%	3.25	West	$A_{GL,W}/A_{GL,TOT}$	-	0.07
B1	DF_{B1}	%	3.30	East	$A_{GL,E}/A_{GL,TOT}$	-	0.00

3. Energy Simulations Aimed at Climate Responsive Design

3.1. Descriptions of the Simulation Scenarios

Context-related guidelines and rules of thumb, reported in literature, have guided the design process of the building presented in the previous section. In this next part, the energy simulation tool allows the optimization and fine-tuning process of the operation schedules and set-points of those components (such as solar shading, operable vents and dimmable lights) which have been embedded with BACS. Energy simulation tools were developed more than thirty years ago and have been perfected ever since. A slightly outdated study, led by Crawley et al. [58] back in 2005, compares some of the best programs at that moment in time, although concluding that none is considerably better than the others; it is therefore suggested to use several tools at once and to cross-check the results for improved accuracy. Nevertheless, energy simulation is used today in the research field mostly, and just barely by professionals, although the EU has recently supported its further adoption thanks to both the EN 52016-1 regulation (Energy Performance of Buildings—Energy needs for heating and cooling, internal temperatures and latent heat loads—Part 1: Calculation procedures) and the EN 52017-1 regulation (Energy Performance of Buildings—Sensible and latent heat loads and internal temperatures—Part 1: Generic calculation procedures), which update the hourly calculation procedures of the old EN 13790 and EN 13791. In this case study, energy simulation is structured according to Scenarios; starting from the reference building "as designed" (Scenario 1), BACS devices are added one at a time (Scenarios 2 ÷ 4) until the aforementioned goals are met.

	Scenario	Automated Component	Strategies
•	Scenario 1—Baseline Building	-	-
•	Scenario 2—Solar Shading	Solar shades	Passive Solar, Daylighting
•	Scenario 3—Natural Ventilation	Operable vents	Natural Ventilation
•	Scenario 4—Daylight Control	Light Controls	Daylighting, Energy Efficiency
•	Scenario 5—Enhanced	All	All

In each Scenario, set-points and schedules are varied within a reasonable range, until improvements in terms of comfort and energy use are achieved, whereas weather data and internal loads are assumed to be invariables. The assessment is based on either thermal comfort or heat balance. All simulations cover a whole reference year, extended of a whole month of warm-up time; further analyses will concentrate on the hourly behavior during selected typical weeks.

3.2. Inputs and References

3.2.1. Climate Data

Energy simulations are based on hourly weather datasets, namely a spreadsheet made up of 8760 entries; to help designers, institutions have come up with several types of reference years, artificially assembled starting from measurements taken throughout many decades.

The most common dataset types are TRY (Test Reference Year), TMY (Test Meteorological Year) and IWEC (International Weather for Energy Calculation). Reference years can also be created following the procedure illustrated in the ISO EN 15927-4/2005 regulation (hygrothermal performance of buildings—calculation and presentation of climatic data—Part 4; hourly data for assessing the annual energy use for heating and cooling). This case-study uses the IWEC dataset for the Porto Airport's weather station (Pedras Rubras) provided by ASHRAE.

3.2.2. Internal Gains

Internal heat gains are caused, at least in buildings such as homes and offices, by occupancy, electronic devices, equipment, and luminaires. As far as the last three categories are concerned, the sensible heat loads are directly proportional to the nominal power and are normally reported as values per floor area unit (W/m^2).

Occupants produce both sensible and latent heat (moisture), both depending on the degree of physical activity and on the amount of clothing he is wearing. Metabolic rate increases with physical activity and is measured in "met" (1 met equals to 58 W/m^2 of body surface, a person averaging around 1.5 m^2); to quiet activities, such as those carried out in the case-study building, correspond around 1.2 to 1.3 met. Occupancy, lighting, and use of devices, variable throughout the day, are therefore quantified by means of schedules, as in Figure 4, and peak loads per floor area unit, as in Table 7.

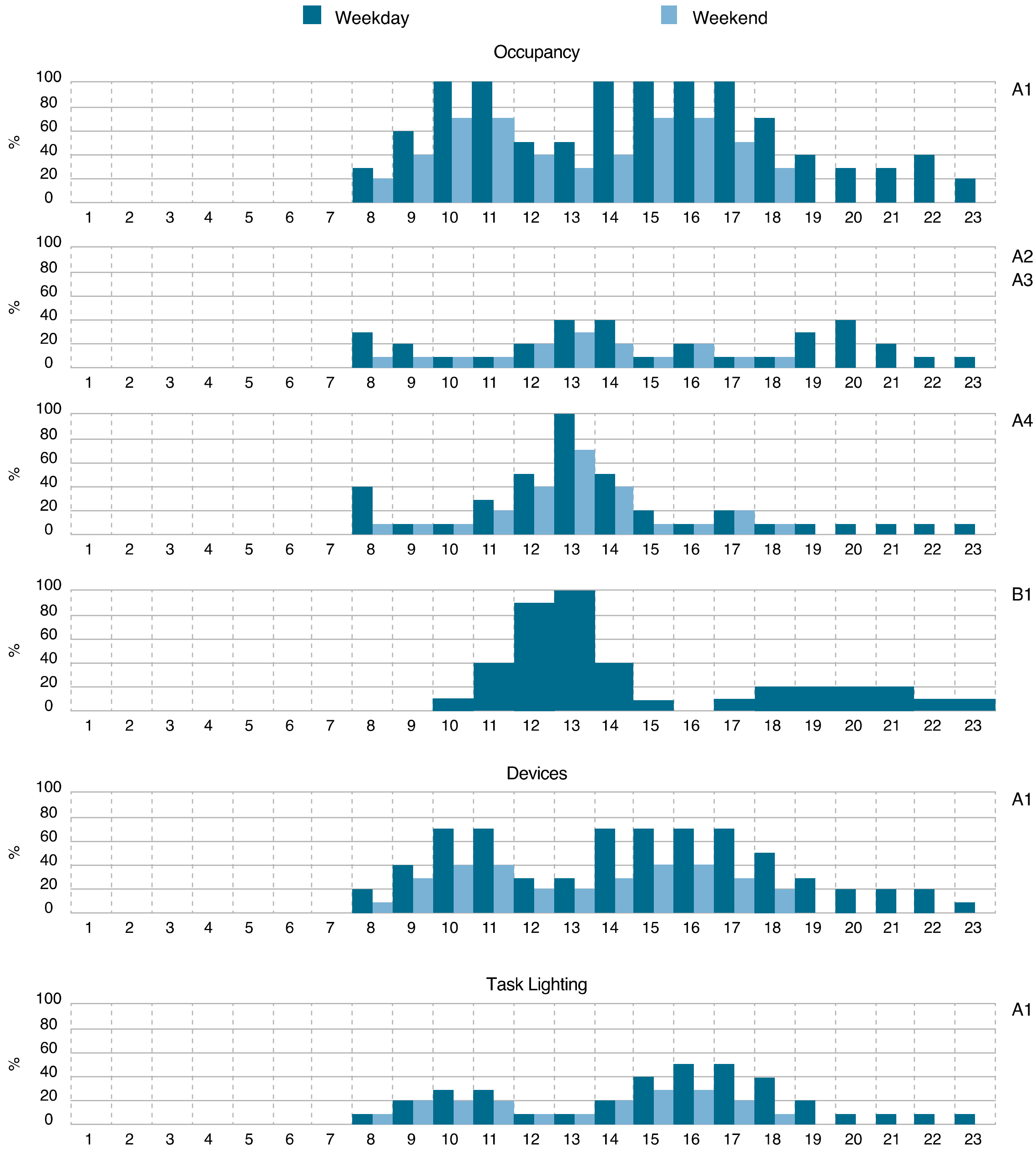

Figure 4. Schedules: Occupancy, devices and task lighting (The ID on the right of each chart refers to the thermal zone, as in the following table. Ambient Lighting in both A and B thermal zones is automatically controlled based on daylight availability; it is therefore not included in schedules. Task Lighting is manually controlled and follows, albeit loosely, the occupancy patterns).

Table 7. Internal gains: Occupancy, devices, and lighting.

ID		**Occupancy**		**Surface**	**Devices**	**Ambient Lighting**	**Task Lighting**
		n°	**W/pers.**	**m^2**	**W/m^2**	**W/m^2**	**W/m^2**
A1	Study room	110	100	370	2.00	4.5	9.0
A2	Hallway	5	110	56	-	2.5	-
A3	Common room	10	150	56	-	5.0	-
A4	Corridor	5	140	166	-	3.5	-
B1	Canteen	240	110	521	-	8.0	-

3.2.3. Comfort Model

Thermal comfort, otherwise described as a feeling of "satisfaction with the thermal environment" [59], is a complex phenomenon, based on quantitative and qualitative factors and usually correlated with other forms of comfort such as acoustic and visual quality of the indoor spaces.

Concerning educational buildings, it is well known that students spent much of their time in schools, thus it is important to provide a good thermal comfort. The thermal environment is particularly important because it is closely related to pupils' health and performance [60]. In facts, poor thermal environments, produce thermal discomfort, and may affect a pupils learning process [60–63].

Today's regulations, such as the ISO 7730/2005 (Ergonomics of the thermal environment—Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria) and the EN 15251/2007 (indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting, and acoustics) take into account two of the most important comfort models: The Fanger model and the Adaptive Comfort model [50,59].

The former sees occupants as passive recipients of given environmental conditions; it becomes less accurate as temperature increases or decreases considerably, being suitable for mechanically conditioned buildings only. The latter assumes that occupants will actively engage in physical, behavioral, and psychological adjustments; as such, it works better in free-running buildings, and is, on this account, adopted in this study. As reported in Table 8, the EN 15251/2007 indicates a proportion between the comfort range ($T_{COMF,MAX}/T_{COMF,MIN}$) and the outdoor running mean temperature (T_{RM}), where the latter may be written with Equation (1):

$$T_{RM} = [(1 - a) \cdot T_{ED\text{-}1}] + (a \cdot T_{RM\text{-}1}) \quad (1)$$

In Equation (1), $T_{ED\text{-}1}$ is the dry-bulb temperature of a previous time interval (i.e., hours, days, weeks), $T_{RM\text{-}1}$ is the outdoor running mean temperature of the previous interval, and "a" is the half-life coefficient, which usually equals 0.8 and weighs the effects of occupant's expectations and time shift. T_{DIFF} is a tolerance, varying according to the building Category (Table 9); in this case-study, Category II is chosen.

Table 8. Adaptive thermal comfort: Temperature range.

T_{RM}	**<10 °C**	**10 ÷ 30 °C**	**>30 °C**
$T_{COMF,MAX}$	24 °C	$0.33 \cdot T_{RM} + 18 + T_{DIFF}$	26 °C
T_{RM}	**<10 °C**	**10 ÷ 30 °C**	/
$T_{COMF,MIN}$	20 °C	$0.33 \cdot T_{RM} + 18 - T_{DIFF}$	

Note—All values are valid for free-running buildings only.

Table 9. Adaptive thermal comfort: Building categories.

Category	**Description**	**PPD**	**T_{DIFF}**
		%	**°C**
I	Special requirements	≤6	2
II	New buildings	≤10	3
III	Existing buildings	≤15	4
IV	Intolerable	≥15	-

Note—PPD (Predicted Percentage of Dissatisfied) accounts for the inevitable percentage of occupants that will be dissatisfied with the thermal conditions.

The resulting comfort range is superimposed as a grey-colored stripe in each of the following temperature charts. For indoor conditions to be deemed comfortable, the indoor operative temperature

(T_{OP}) must fall within the comfort range. T_{OP} accounts for both conductive and radiative heat transfer, and may in general be expressed with Equation (2):

$$T_{OP} = (h_R \cdot T_{MR} + h_C \cdot T_{AIR})/(h_R + h_C) \tag{2}$$

where T_{MR} is the Mean Radiant Temperature, T_{AIR} is the Indoor Air Temperature, and h_R and h_C are respectively the radiant and convective heat transfer coefficients. When the air speed is below 0.1 m/s and the metabolic rate is between 1.0 and 1.3, T_{OP} may be rewritten with Equation (3):

$$T_{OP} = (T_{MR} + T_{AIR})/2 \tag{3}$$

4. Results and Discussion

In this Subsection, BACS are introduced one at a time in order to control the activation schedules, the set-points and operations of those building components, whose features directly influence the global building behavior.

From here onwards, the analysis are only focused on the most significant and yet critical thermal zone; the study room (A1). As already stated, simulations are assessed considering the indoor operative temperature profiles (compared to thermal comfort range) and the main heat losses and gains. In detail, the indoor operative temperature profiles are calculated using daily averaged values obtained from the hourly step based simulations. The operative temperature profiles are referred to free run conditions, taking into account only the BACS considered for each Scenario. When the operative temperature falls outside the thermal comfort range, the HVAC systems considered turned on and the related energy consumptions were computed.

4.1. Scenario 1—Baseline

The Baseline scenario represents the reference building as designed (see previous Section), according to the bioclimatic guidelines and rules of thumb found in literature [23,29] and devoid of any kind of automation device. Figure 5 shows the daily mean indoor operative temperature profile, together with the main heat losses and gains; in the first chart, the temperature rises up to 35 °C and stays above the comfort range even during winter. The main sources of excess heat are irradiation (through glazing), occupancy and lighting. This first evaluation serves as the basis for the following Scenarios: Automated solar shades are introduced in Scenario 2, automated operable vents (Scenario 3), and daylight-dependent dimmable light controls (Scenario 4).

4.2. Scenario 2—Solar Shading

Solar shading is one of the simplest and yet most effective strategies for minimizing overheating and keeping temperatures within the comfortable range. In this case-study building, windows and skylights were fitted, outside and inside respectively, with automated roller shades, whose transmission coefficient is set to 30%. Shades are operative from April through September, according to the schedule contained in Table 10a,b; their activation, though, is based on either air temperature or incident solar radiation.

Four set-points were chosen for solar radiation (100-200-300-400 W/m^2, although only the first and last are shown in the charts) and two for air temperature (T_{IN} = 26 °C; T_{OUT} = 20 °C). Both systems achieve positive results in terms of daily mean indoor operative temperatures (as in Figures 6a and 7a) thereby improving indoor comfort conditions. However, as regards the heat transmission, and solar gains in particular (Figures 6b and 7b) temperature-based control does not guarantee as steady a result as radiation-based control. In light of this, radiation-based control will be employed for solar shading from here onwards.

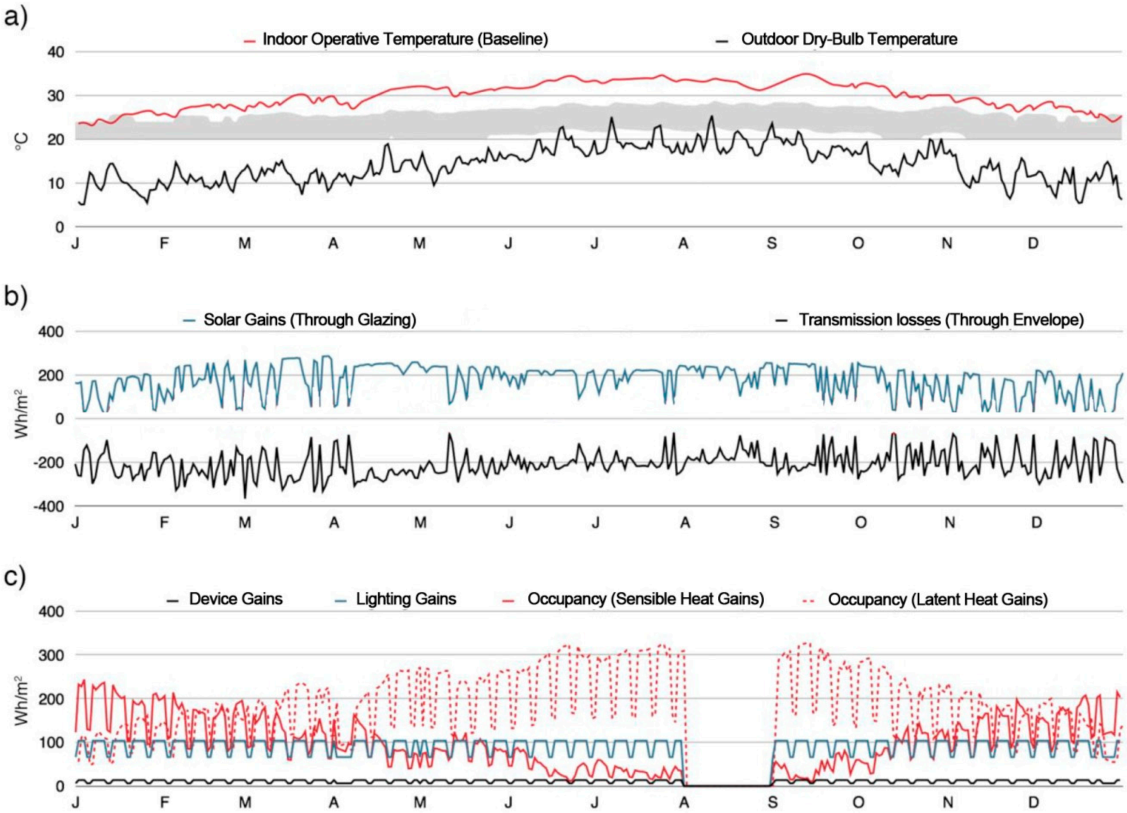

Figure 5. Scenario 1: Baseline: (**a**) Temperature profiles; (**b**) external heat losses and gains; and (**c**) internal heat gains.

Table 10. Scenario 2 ÷ 4: Schedules.

	J	F	M	A	M	J	J	A	S	O	N	D
(a) Solar shading—Radiation control												
Operation	Off			On						Off		
Set-points—Solar radiation [W/m^2]	100-200-300-400											
(b) Solar shading—Air temperature control												
Operation	Off			08:00–19:00						Off		
Set-points—Air temp. [°C]	26 (indoor)—20 (outdoor)											
(c) Natural ventilation												
Operation	08:00–19:00			08:00–24:00						08:00–19:00		
Set-points—Air temp. [°C] Case 1	20		24		26				24		20	
Set-points—Air temp. [°C] Case 2	22			24						22		
(d) Mechanical cooling												
Operation	On											
Set-points—Air temp. [°C]	26											
(e) Daylight control												
Operation	On											
Set-points—Illuminance [lx]	Table 3											

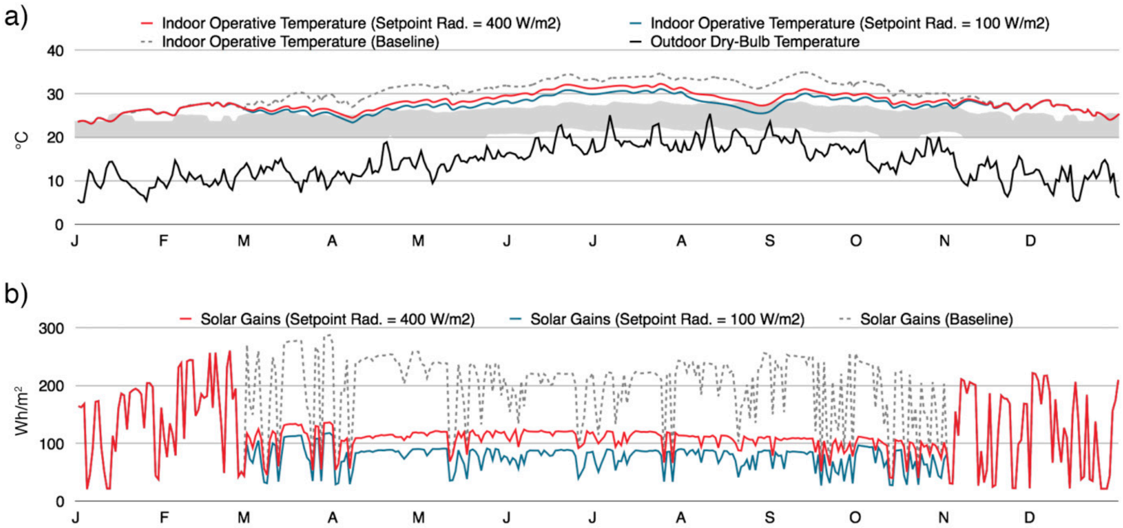

Figure 6. Scenario 2: Solar Shading (Radiation-based): (**a**) Temperature profiles; and (**b**) solar gains.

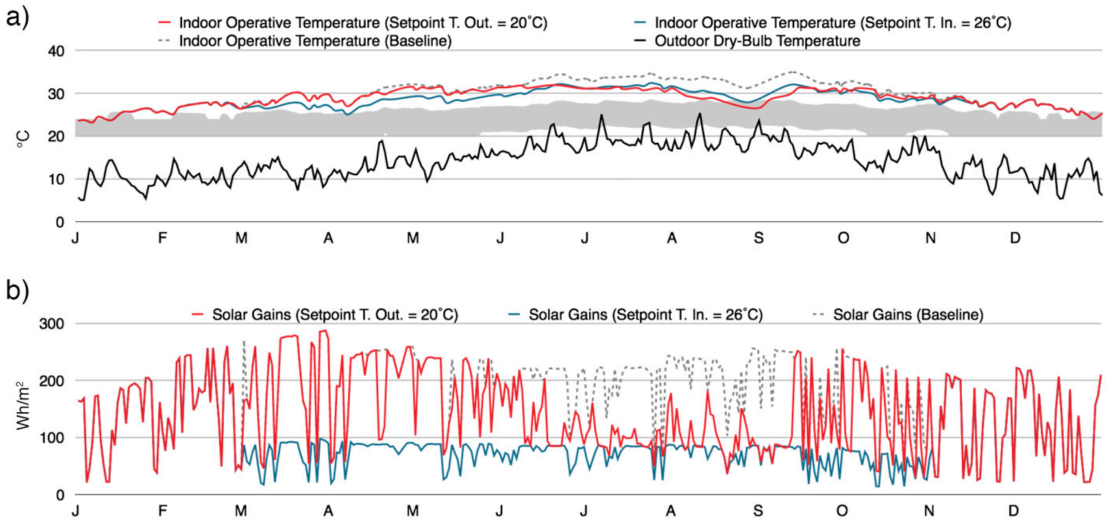

Figure 7. Scenario 2: Solar Shading (Temperature-based): (**a**) Temperature profiles; and (**b**) solar gains.

4.3. Scenario 3—Natural Ventilation

As pointed out by Olgyay [23], ventilation extends the comfort range upwards, favoring transpiration and therefore the human body's ability to withstand humidity. EnergyPlus breaks this complex phenomenon down into a system of nodes, constraints and paths, otherwise referred to as the "Airflow Network Model". In the case-study building, operable vents were placed on the Northern and Southern sides of the building. While they are operative all year-round (during selected time-slots, as in Table 10c), their actual use depends on indoor air temperature set-points (Case 1 and Case 2). An additional infiltration rate, inevitably caused by porosity, cracks and poor joinery, is set by default on $10^{-3} \div 10^{-5}$ kg/(m·s·Pa), depending on the envelope component. In a cool and windy climate, such as that of Porto, the effect of natural ventilation is truly remarkable; the daily mean indoor operative temperature is lowered into the comfort range (Figure 8a), while latent occupations gains are consistently reduced (Figure 8b), as opposed to the first scenario (Figure 5c). If natural ventilation were unable to productively cool the building below 26 °C (when the outdoor temperature, for instance, is higher than indoors, or there is simply not enough wind), an air conditioning system will step in.

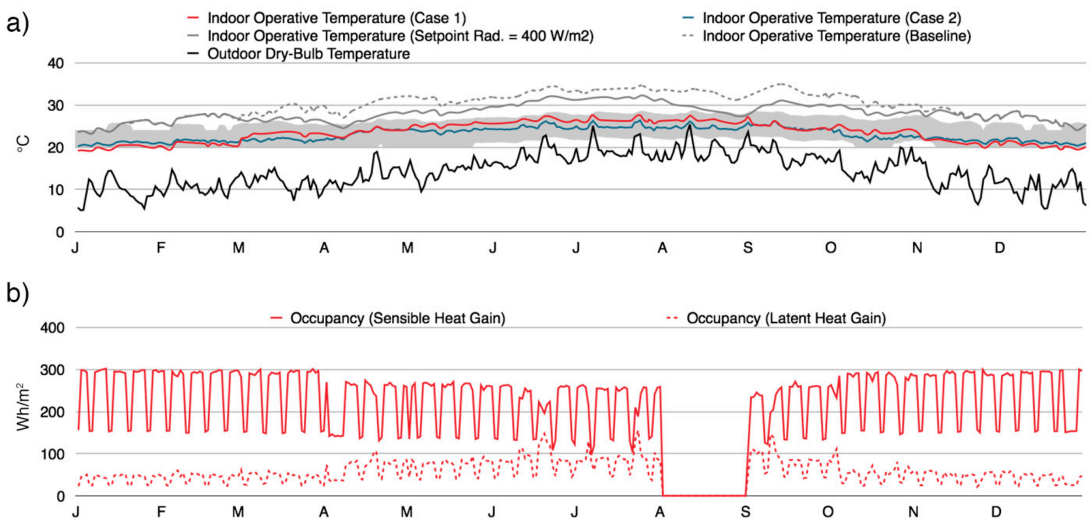

Figure 8. Scenario 3: Natural Ventilation: (**a**) Temperature profiles; and (**b**) occupancy gains.

4.4. Scenario 4—Daylight Control

Daylighting is inevitably related to architectural design, as windows must be sized and placed in such a way as to avoid direct sunlight, over-lighting, and glare; if well implemented, it reduces lighting loads and therefore energy use. BACS regulate the power supplied to the lights according to variations in the availability of daylight (illuminance measured on selected work planes) during the course of the year. Figure 9 compares the lighting gains of the case-study building when Daylight Control is enabled or disabled respectively; the result is obviously achieved in summer, when daylight is available all throughout the day.

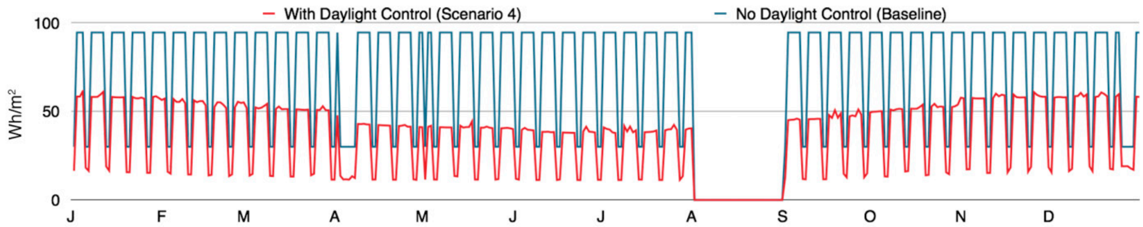

Figure 9. Scenario 4: Daylight Control. Lighting Gains.

4.5. Scenario 5—Enhanced

The final Scenario is nothing but a summary of the previous ones, as it brings all the individual strategies together into an integrated design; actual set-points are reported in Table 11. According to Figure 10a, which compares both the first and last Scenario, positive results were achieved in terms of daily mean temperature profiles. Figure 10b displays an overall energy balance for the whole reference year.

Table 11. Scenario 2 ÷ 4: Selected set points.

Strategy		Thermal Zones		
		A1/A2/A3	A4	B1
Solar Shading	W/m^2	100	X	400
Natural Vent.	°C	22/24	X	22/24
Mech. Cooling	°C	26	26	26
Daylight Control	-	V	V	V
Infiltrations	-	V	V	V

Note: "V" and "X" are used for a strategy which does not present set-points of schedules, and indicate, respectively, whether it has been adopted or not.

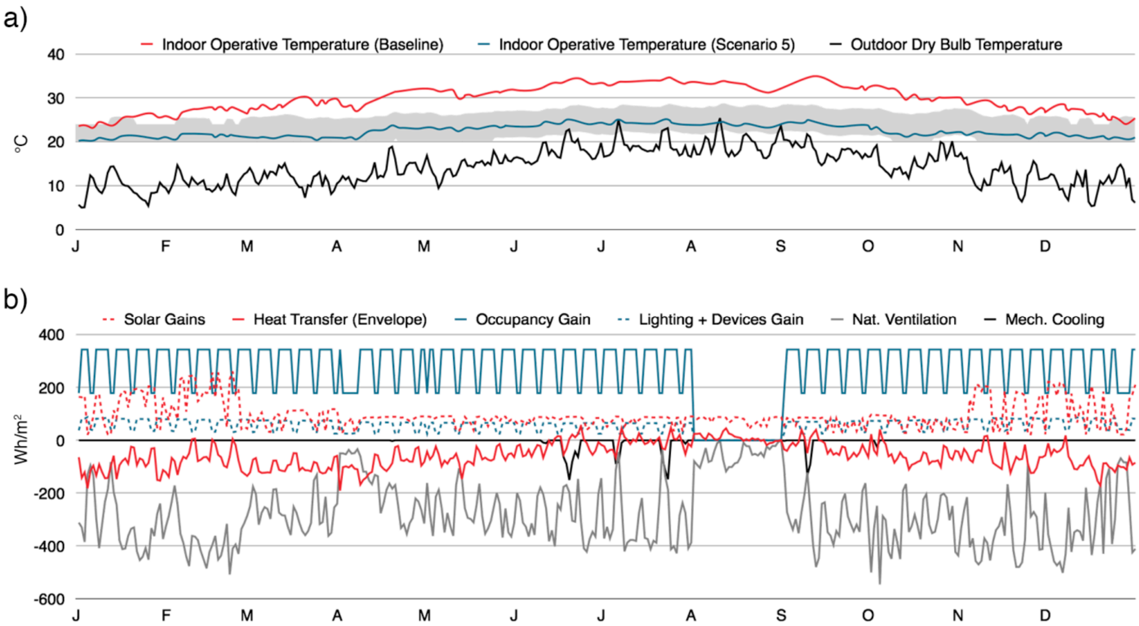

Figure 10. Scenario 5: Enhanced: (**a**) Temperature profiles; and (**b**) overall heat balance.

The hourly temperature profile and energy balance for selected typical weeks are previously shown. Energy simulations also ascertained that, based on an opening time of 4800 h on a yearly total of 8760, the Enhanced Scenario conforms to the Adaptive comfort model for more than 98% of the time; by comparison, the Baseline Scenario was found to comply only in 5% of the same time frame. Energy end-use calculations did not linger on less relevant shares such as domestic hot water (DHW), outdoor lighting and emergency lighting, but focused on plug loads (devices, such as laptops), indoor lighting, HVAC and BACS. All things considered, the overall reduction in electrical energy end-use between the Baseline Scenario and the Enhanced Scenario, was estimated to be around 53%, as in Table 12. Unfortunately, both the annual energy end-use of Porto School of Architecture's existing premises and the average annual specific energy use of buildings of the same type and size in this region of Portugal were not available to the authors. As a comparison, an Italian study by ENEA (the Authority for Energy, Environment and New Technologies) [64] estimated the annual primary and final energy use in public schools and offices across Italy. Its authors acknowledge that potential savings in electrical energy up to 23% could be achieved thanks to renovations.

Table 12. Energy end-use calculations in the five Scenarios.

Scenario		Average Operative Temperature (°C)	Energy Use (kWh/m^2·year)			
			Lighting	HVAC	BACS	Total
1	**Baseline**	30.1	24.9	8.2	0.0	34.3
2	**Solar Shading—radiation based**	28.8	26.2	3.5	0.6	30.3
	Solar Shading—temperature based	29.3	25.9	3.9	0.6	30.4
3	**Natural ventilation**	24.8	24.9	5.1	0.6	30.6
4	**Daylight control**	29.5	11.4	8.0	0.6	20.0
5	**Enhanced**	22.4	12.7	0.2	1.8	15.9

4.6. Hourly Breakdown

A more detailed analysis examines the results on a daily basis, focusing on two typical weeks; from the 15th to the 21st of January and from the 22nd to the 28th of July. Only such an in-depth examination can detect the temperature swings over the course of a day and correlate the phenomenon to changes in energy balance. As expected, both in summer and winter-time ("a" and "b", respectively, in each of the following charts), the hourly indoor operative temperature always falls within the predetermined comfort range (Figure 11).

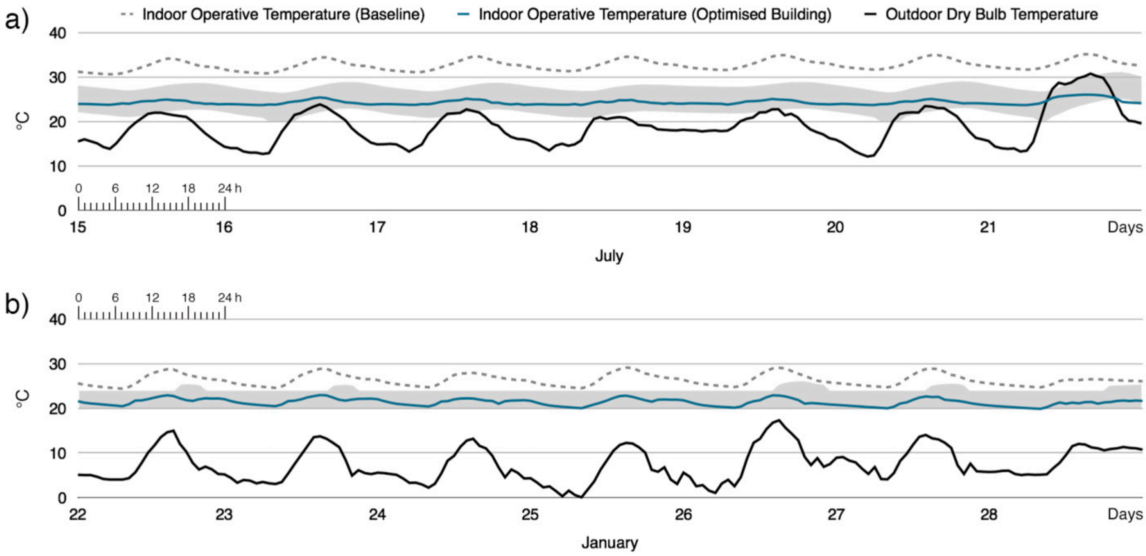

Figure 11. Scenario 5: Enhanced. Hourly Temperatures: (**a**) July; and (**b**) January.

In Figure 12, the hourly energy balance confirms a reduction of both the internal and envelope (external) gains; the quite large heat gain caused by occupation is, instead, counterbalanced by natural ventilation.

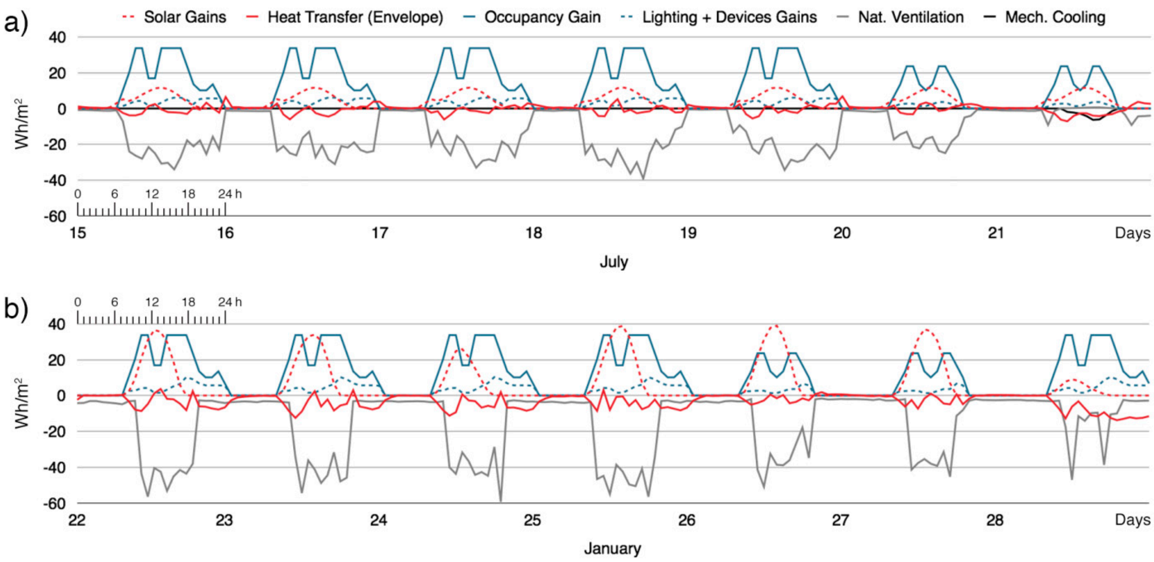

Figure 12. Scenario 5: Enhanced. Hourly Energy Balance: (**a**) July; and (**b**) January.

In this regard, Figure 13 contains the actual hourly air change rates due to natural ventilation; even though the air renewal rate is almost as close (if not higher) to the minimum levels contained in regulations (in this case, for the A1 thermal zone) natural ventilation will have to be supported by mechanical ventilation in order to avoid unpleasantly cold draughts and excessive air velocity.

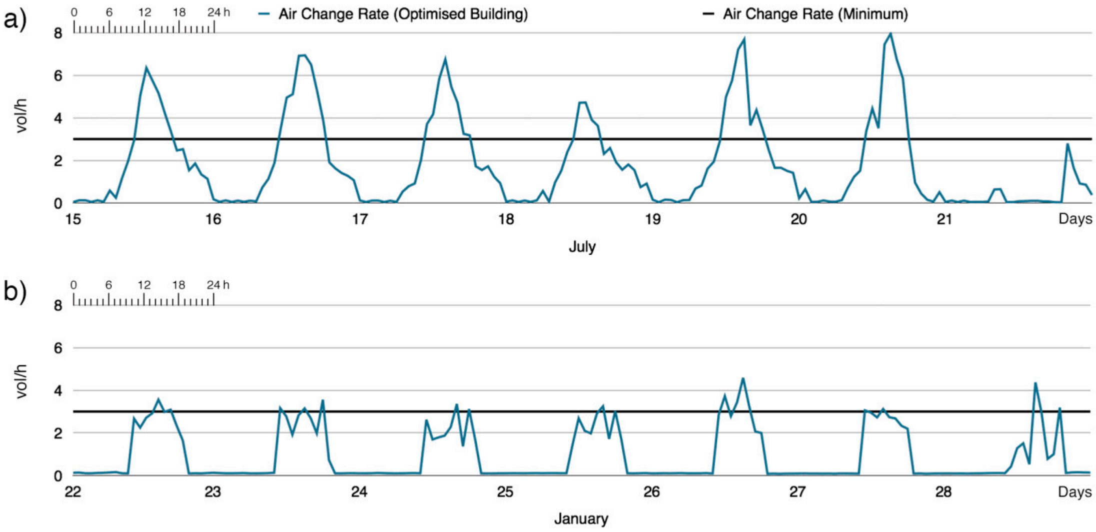

Figure 13. Scenario 5: Enhanced. Hourly Air Change Rate: (**a**) July; and (**b**) January.

5. Conclusions

The last century of human history has taught us that climate change is an issue that we can't ignore any longer, and that, on the contrary, we must strive to reach sustainability. For some thirty years, following in the footsteps of worldwide and international agreements, far-sighted legislators have been making a difference by calling for energy-efficient constructions and by promoting a shift in the people's mind-set.

Among other measures, the EU has recently introduced the Nearly Zero Energy Building, or "nZEB", a regulatory concept, whose proper definition has been left to national regulations. Beside this, however, voluntary systems, based either on performance or rating, have spread all over the place; the result is a very confusing state of affairs, as both systems fail to address the pressing issues that belong in the beginning of the design process.

Bioclimatic design, instead, looks at the subject from a different perspective; a context-based building, the result of an empirical expertise, takes advantage of the local environment, making do without complicated mechanical systems and relying instead on passive design. While frequently associated with low-tech construction or emergency architecture, this kind of design can indeed benefit from the integration with state-of-the-art technology, such as Building Automation Control Systems. This approach has been employed in the design of the new wing of Porto's School of Architecture; it comes in the shape of a partially underground building, which houses a new canteen, a study room and a parking lot. The energy simulation of this case-study building confirmed the previous assumption, as remarkable improvements in terms of indoor thermal comfort and energy end-use were achieved as soon as building automation was introduced.

The process reported in this paper, which introduces building automation and energy simulation into bioclimatic architectural design, can be scaled and repeated indefinitely, regardless of building size or type. In conclusion, it constitutes an important precedent to look to for any designer of energy-efficient buildings.

In order not to be distracted, some less relevant topics had to be disregarded; as such, they can be considered the starting point for further investigations. These include the optimization of the envelope assemblies, the effect of thermal bridges and that of ventilated thermal mass. As far as IEQ is concerned, CO_2 levels shall be taken into account when it comes to natural ventilation; this, in turn, needs to be supported by mechanical systems in order to provide a steady ACH. Moreover, on-site energy generation must be investigated, in order to determine whether the building achieves an nZEB condition or not.

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