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Review of bioclimatic architecture strategies for achieving thermal comfort

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ABSTRACT

The residential sector consumes a significant amount of energy worldwide. Therefore, it is important to study, analyse and implement bioclimatic architectural systems that contribute to the reduction of energy consumption while considering the possible construction solutions offered at both passive and active levels. The present study conducted a comprehensive analysis that was stratified into three large blocks. The first block examined the concept of bioclimatic architecture. The second examined the bioclimatic architecture construction strategies as a function of each climate zone with the objective of achieving the greatest climate comfort level within a specific building. Fourteen climate zones were established and recommended according to the possible strategies that would facilitate reductions in energy consumption. The third block analysed the principal scientific research trends in this field and highlighted the use of vernacular architecture strategies, experimentation with bioclimatic architecture construction, application of innovative bioclimatic architecture strategies, promotion of bioclimatic architecture, use of bioclimatic architecture in urban planning, inclusion of bioclimatic lessons in study plans and development of energy saving technologies to support bioclimatic architecture. The extensive review described in this paper allowed us to conclude that certain bioclimatic architecture strategies that have been adopted in specific countries could be exported to other areas with similar climates because they were proven to be good functional design strategies that resulted in large energy saving measures (each in its corresponding climate) related to solar protection, humidification or temperature increases.

Contents

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1. Introduction

Human health and comfort have been perceived as the most important parameters during evaluations of indoor environments. Developing countries are limited by extreme environmental conditions, out-dated construction techniques and scarce financial resources and therefore struggle to adopt costly technologies aimed at achieving improved interior environments [1]. Any analysis of the role of energy in architecture is faced with serious limitations due to the lack of such studies in the architectural literature. An awareness of these limitations will enable one to understand why architects have paid little attention to the interaction between form and energy and a bioclimatic focus in contemporary architecture [2]. The construction sector plays an important role in the European economy, as it generates nearly 10% of the gross domestic product and provides 20 million jobs that are concentrated among small and medium-sized businesses [3]. The intense building construction activity, the need to conserve energy and the establishment of environmental protection policies all indicate a need for more reasonable building design practices [4]. The heating and cooling of a space to maintain thermal comfort are an energy intensive process that represents up to 60–70% of the total energy consumption in non-industrial buildings [5]. The concept of energy efficiency in buildings refers to the amount of energy required to achieve the desired environmental conditions while minimising energy consumption [6]. Heating, ventilation and air conditioning (HVAC) are the largest energy consumers in buildings [7]. Ekici and Aksoy [8] listed the parameters that affect building's energy requirements as follows: physical–environmental parameters (daily exterior temperature, solar radiation and wind speed and direction) and design parameters (shape factors, surface transparency, orientation, thermal–physical construction material properties and distances between buildings). The term bioclimatic (or sustainable) architecture refers to an alternative method of constructing buildings in which the local climate conditions are considered and diverse passive solar technologies are used with the aim of improving energy efficiency [9]. The term solar passive technologies refers to heating or cooling techniques that passively absorb (or protect, e.g. natural hats) the sun's energy and contain no moving parts [10]. Bioclimatic design employs appropriate technologies and design principles based on a reflexive focus on the climate and environment

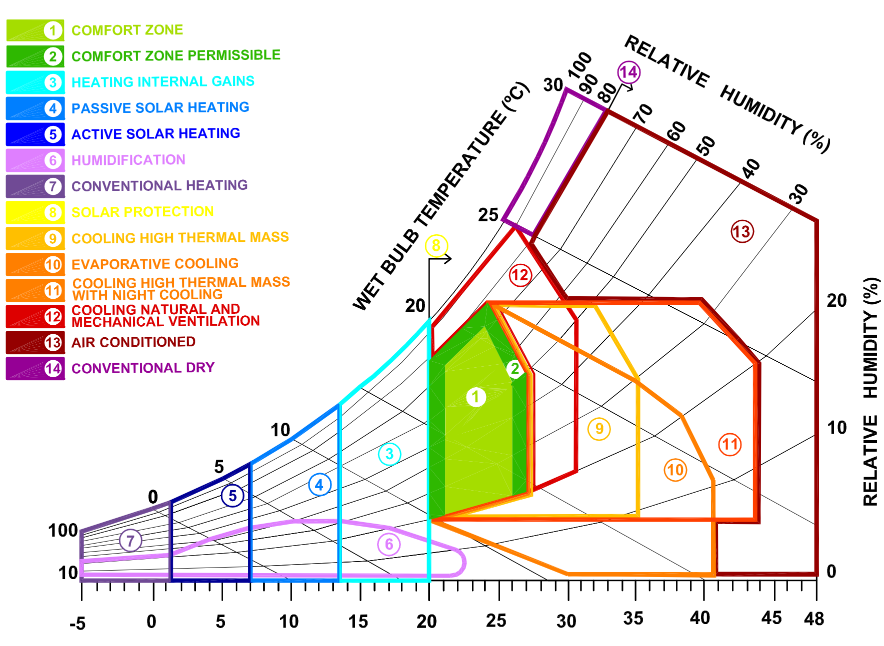

Fig. 1. Psychrometric chart adapted from Givoni [30].

[11]. The application of bioclimatic principles is a critical factor in reducing the energy consumption and CO_2 emissions of the construction sector [10].Such design concerns the disposition of buildings (orientation related to the sun and wind, aspect ratio), space (site planning), air movement, openings (size-position, protection) and the building envelope (walls, construction material-thickness, roof construction detailing) [11]. As people spend more than 80% of their lives within buildings, the environmental comfort in a workplace is strongly related to the satisfaction and productivity of its occupants. However, energy consumption is known to be directly and strongly related to the exploitation costs of a building. Therefore, energy consumption and environmental comfort measures are often in conflict [4]. This paper intends to describe the architectural strategies employed in bioclimatic architecture and analyse the existing trends. To that end, we have surveyed published articles on the subject.

2. A brief overview of the bioclimatic architecture concept

The mission of architecture has always been the protection of man from the exterior environment and in this case, bioclimatic architecture attempts to achieve human thermal comfort by interacting energetically with the exterior climate. Architecture has always held the objective of climate comfort and this has been inherent to architecture from its origins. Throughout history and in every place and climate, architectural evolutions have occurred to achieve the best comfort levels in interior spaces; this process has been termed “vernacular architecture”, of which we still find many worthy examples to study, including those in India [12], China [13] or Iran [14,15].

Since the Industrial Revolution, and with the concept of function-shape, comfort in modern architecture has been relegated to the use of devices that continuously consume energy and have an ecological footprint [16]. From that period, the interaction between shape and energy was set aside [2] and a shift was made to an indifferent architecture based on intensive energy consumption technologies. In the 1980s, the environmental damage produced by buildings was recognised, giving rise to the concept of sustainability [17]. Currently, after observing the local and global environmental effects and after directing the global consciousness towards sustainability, there has been a return to the values of architecture associated with the broad term of “commodities”, which was coined by [18].

Vernacular architecture is in a developmental process intended to reclaim the architectural values of protection against the severities of the exterior climate in accordance with the objective of minimal consumption (to near-zero if possible). We can highlight, for example the new emerging vernacular of self-built urban settlements in Brazil [19]. During these times of environmental crisis and accelerated urban development, it seems logical for architects to practice sustainable ecological design [20]. Bioclimatic adjustments basically comprise three directions: energy, human health/wellbeing and sustainability [17].

To apply bioclimatic architecture, it is necessary to consider the various climate levels of the building's location, including the general climate, the mesoclimate and the climate near the building defined by the nearby elements or microclimate [21]. The next step would include the architectural skin, which requires accounting for the temperature, relative humidity, solar radiation and albedo, as well as the wind speed and direction, as the elements to consider when striving for comfortable conditions [22]. Human thermal comfort can be defined [23] as a condition of mind that expresses satisfaction with the thermal environment [24] such that the person would prefer neither warmer nor cooler surroundings [25]. Comfort can also be defined as the optimal thermal condition in which the least extra effort is required to maintain the human body's thermal balance. Various environmental factors (air temperature, surrounding surface temperatures, air humidity and air velocity) and psychosocial factors (clothing, activities, age and sex) affect human comfort [26].

Different bioclimatic diagrams are used as tools with which to determine comfort levels. The most widely used include the diagram developed by Victor Olgyay [27,28] to determine exterior comfort as well as diagrams for interior comfort, including the thermal comfort index (or effective temperature), which can be calculated using the relative humidity and interior temperature values and has been adopted by ASHRAE [29] and, based on the same parameters, the diagram by Baruch Givoni [30] (Fig. 1). Some of the intervals for the external comfort parameter values that interact to determine thermal comfort are shown in the bioclimatic diagrams and include an ambient air temperature between 18 and 26 °C, a mean radiant temperature on building surfaces between 18 and 26 °C, an air velocity between 0 and 2 m/s and a relative humidity between 40% and 65%.

3. Bioclimatic architectural strategies

The Givoni diagram, shown in Fig. 1, is a bioclimatic diagram that has been divided into different zones for which it is necessary to use strategies to achieve human comfort within a building [31]. The x-axis represents the dry bulb temperature and the y-axis shows the fresh air humidity; psychrometric curves in the graph represent the relative humidity. For example, Rupp and Ghisi [32] have used this diagram to evaluate the thermal comfort during the summer in hybrid commercial buildings located in a warm and humid climate. As stated in the above-mentioned figure, 14 zones are defined based on previous definitions of bulb temperature and fresh air humidity. From these, zones 1 and 2 are the ideal comfort zones. Thus, we can define climatic conditions and the associated architectural strategies to shift the environmental conditions of the home into the comfort zone. Whenever possible, passive strategies will be proposed, as these consume zero energy. When this is not possible, these strategies will be applied to help reduce the use of energy consuming devices to the lowest possible levels.

To study the possible bioclimatic architectural strategies, we must first evaluate the conditions in which the home is located. The environmental conditions will place us within a zone in the Givoni diagram (Fig. 1). If we are in the comfort zone, architecture will not have to perform any thermal corrections. If we are outside of the comfort zone, architectural strategies can be implemented to reach the comfort zone.

3.1. Comfort and permissible comfort zones

The comfort zone, labelled as zone 1 in Fig. 1, exhibits the ideal conditions for the human body. Statistically speaking, this zone is comfortable for 70% of the population [33]. It represents the area in which the human body, with light clothing and little activity, does not require energetic expenditures to remain comfortable. This zone is bound by temperature values between 21 and 26 °C and relative humidity values between 20% and 70%. No strategies need to be implemented in this zone.

The permissible comfort zone is a larger comfort zone in which a person no longer has zero expenditure but can adapt with an acceptable minimum expenditure. This zone is comfortable for 80% of the population [33]. The temperature and humidity conditions are also acceptable for certain human bodies depending on sex, internal metabolism, size and activity performance. As shown in Fig. 1, this area is labelled as zone 2 and is bound by temperature values between 20 and 27 °C, relative humidity

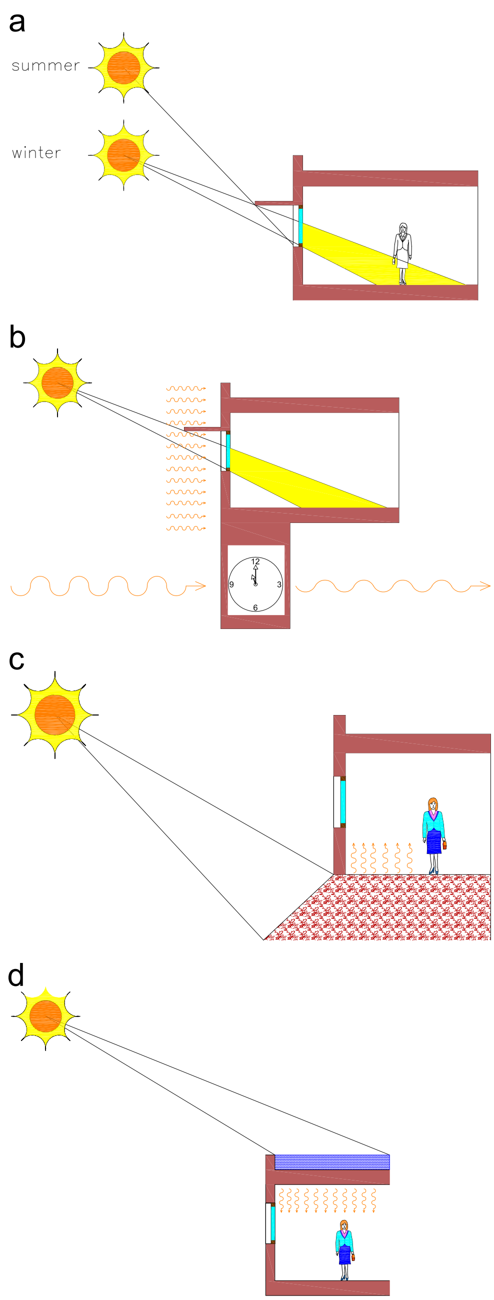

Fig. 2. Passive solar heating techniques (I): (a) The awning as a passive solar heating solution; (b) representation of radiation capture through openings for a space in the passive solar heating zone. The clock indicates the possible phase difference of up to 11 h for heat transmission; (c) representation of capacitive flooring for a space in the passive solar heating zone and (d) roof pond for a space in the passive solar heating zone.

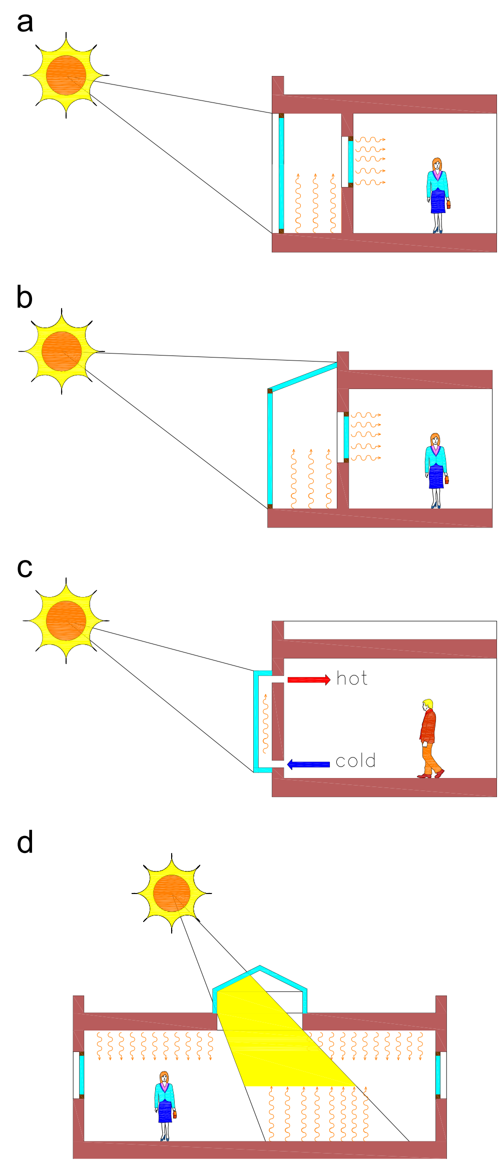

Fig. 3. Passive solar heating techniques (II): (a) Representation of a glassed-in gallery for a space in the passive solar heating zone; (b) representation of an adjoined greenhouse for an area in the passive solar heating zone; (c) representation of a Trombe wall for an area in the passive solar heating zone; and (d) representation of roof openings for a space in the passive solar heating zone.

values between 20% and 80%, and a line between the intersection of 24 °C temperature and 80% relative humidity and the intersection of 27 °C temperature and 50% relative humidity.

3.2. Heating internal gains

In this zone, internal gains are important in order to vary the temperature and move it nearer the comfort zone. This zone, labelled zone 3 in Fig. 1, is defined by temperature values between 13.5 °C and 20 °C. Internal gains are provided by people who occupy the same space, artificial lighting, any machinery that generates heat energy and any process that might also generate heat. This internal gain is only due to temperature differences and is described as a sensible load, an important parameter for the climatic calculation of a building.

3.3. Passive solar heating

The term 'passive' relates to building envelope design, whereas 'active' heating relates to the use of any external energy source, other than solar thermal energy, used for building air conditioning or even solar heating [7]. Passive solar heating has been used extensively throughout history with great success [34].

This zone is defined by temperatures between 7 °C and 13.5 °C (see zone 4 in Fig. 1). To move towards the comfort zone, it is necessary to have a solar absorption strategy that allows heat energy gain within the space. The intent is to increase the temperature from 7 °C to above 13.5 °C. To that end, the fundamental objective is that the building design will favour the accumulation of solar radiation and will subsequently distribute this energy to other dependencies or return it to the building over

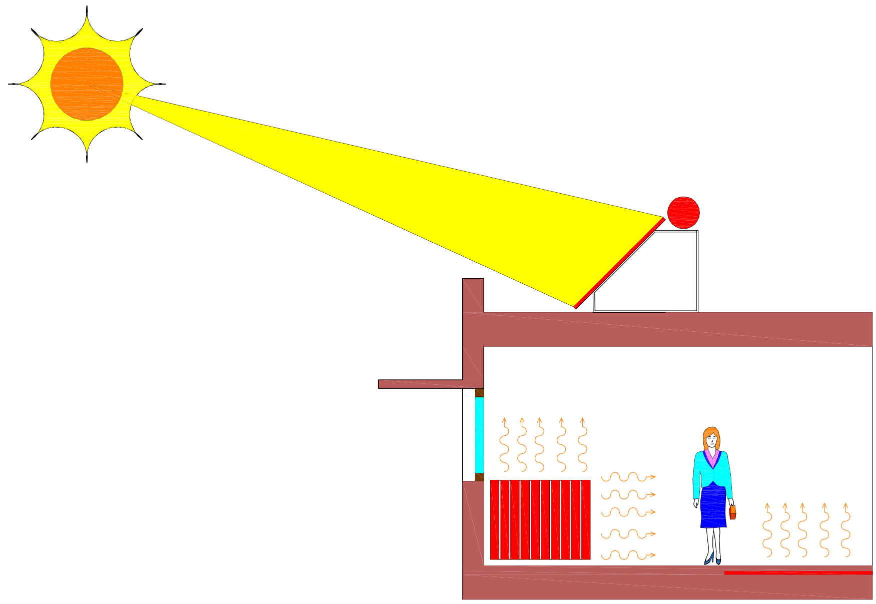

Fig. 4. Active heating techniques.

time. The energy distribution can be direct through radiation (temperature gradients) or convection (warming of air in contact with the emitting terrain), or indirect by forcing air through accumulating elements and subsequently forcing the air to circulate in the space. Different solutions are provided in this zone because the energy can be captured by any part of the building envelope, including the soil, walls, roof and especially openings. The latter can allow the entry of radiation during times when it is needed and prevent this radiation from escaping the building through the use of, for example, carpentry and appropriate glass windows. The large windows on the south-oriented façade of a passive house strongly contribute to building space heating [35]. Fig. 2(a) shows an example of an awning in warm areas that allows solar radiation capture during the winter season and limiting this process during the summer. Thus, the building openings can facilitate the entry of solar radiation for storage in the building flooring that can be returned with a time phase difference.

Energy storage in the walls, ceilings and floors of buildings can be enhanced by encapsulating suitable phase change materials (PCMs) within these surfaces to directly capture solar energy and increase human comfort by decreasing the frequency of internal air temperature shifts and maintaining a temperature nearer the desired temperature for a longer period of time [36]. PCMs play a very important role in energy conservation [37]. The research by [38–40] studied PCMs and extensively reviewed the corresponding material properties for the application of these materials for thermal storage in buildings. Some PCMs exhibit a phase difference exceeding 11 h, meaning that heat energy captured during the day is returned during the night (Fig. 2(b)).

Capacitive flooring (Fig. 2(c)) and roofs (Fig. 2(d)) become charged with heat energy from solar radiation and later emit this energy to their connected spaces. In the case of flooring, we must highlight the great importance of the thermal stability of the ground as an example in subterranean buildings such as caves [41]; this also applies to underground basements and semi basements [42–44].

For roofs, the most frequent case is that of the water roof (Fig. 2(d)), which modulates the interior temperature. This solution is generally adopted in hotels in warm areas that place swimming pools on rooftops to assist with climatisation of the top story of the building, among other reasons. To a lesser degree, green roofs also help to reduce the energy demand.

Glassed-in galleries (Fig. 3(a)) are architectural elements that capture solar radiation during cold seasons and maintain the energy by using enclosures, floors and generally capacitive materials, which later return the energy with a phase difference. The adjoined greenhouse (Fig. 3(b)) is a very similar bioclimatic strategy that captures even more solar radiation because of its transparent top surface. In significantly colder areas, the greenhouse strategy is more appropriate than the previous strategy. Another very similar strategy is the Trombe wall (Fig. 3(c)). The classical Trombe wall is a massive wall covered by exterior glazing with an air channel between the layers; the glass is so near the wall that it becomes part of the façade and leaves no habitable space between the layers. This massive wall absorbs and stores the solar energy through the glazing. Some of this energy is transferred through the wall into the indoor area of the building (the room) by conduction. Meanwhile, the colder air enters the air channel from the room through a lower wall vent, is heated by the wall and flows upward due to buoyancy [7].

Roof openings are other elements that allow the entry of solar radiation to facilitate the accumulation of heat energy in capacitive materials. Examples include skylights that cover patios adjacent to living spaces (Fig. 3(d)). These living spaces are favoured by the heat provided by solar radiation, which accumulates in the patio. In warmer months, these openings must be covered to avoid excessive radiation. This strategy is very common in Southern Spain.

3.4. Active solar heating

The objective of active solar heating is similar to that of passive solar heating; however, in the case of active heating, a fluid is heated and later heats the interior of the home. Occasionally, a small amount of energy is required to drive and distribute this heat gain because the climate conditions correspond to temperature values between 1 and 7 °C (see zone 5 in Fig. 1). Passive systems alone cannot achieve comfortable conditions in the space but can help reduce energy consumption. In such cases, architectural elements should be designed to allow radiation entry during times when is necessary and prevent this radiation from exiting the building envelope. This requires a focus on the walls, roofs and especially openings, where appropriate carpentry and glass

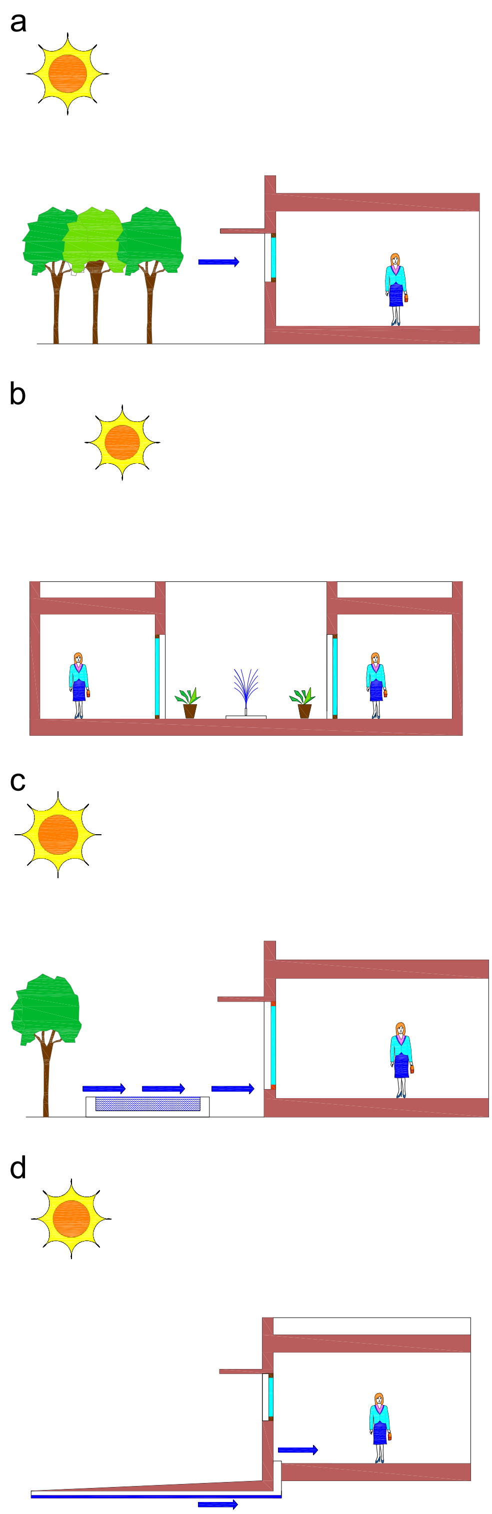

Fig. 5. Humidification techniques: (a) Example of air humidification through contact with vegetation; (b) example of air humidification through contact with vegetation within the building (patio); (c) example of air humidification through contact with accumulated water; and (d) example of air humidification through contact with water in buried pipes.

windows are important. In addition, energy can be captured in the building using low temperature solar thermal cells or photovoltaic cells, which produce electricity for conventional thermal conditioning systems. Energy distribution is conducted through installed radiant heated floors or radiators and the energy is generally shared with the installed water heater system (Fig. 4).

3.5. Humidification

A lack of air humidity can produce respiratory disorders in humans by causing excessive respiratory pathway dryness and can also induce dermatitis, which is characterised by dry skin. For this reason, it is necessary to supplement the indoor air with water vapour in certain climate zones. The objective of this strategy is to achieve comfort by raising the relative humidity. This is accomplished by introducing air that has passed over a water surface. This air can be moved by differences in pressure (passive) or by mechanical devices (active). This strategy corresponds to the temperature zone of up to 22.5 °C; the relative humidity levels are variable but can reach 40% at 10 °C (zone 6 in Fig. 1).

The most common bioclimatic architecture strategies aim to introduce humidity through air drafts, for which it is necessary to consider the dominant air movement conditions in order to provide humidity to the surrounding rooms. The most frequent strategies include the presence of vegetation near (Fig. 5(a)) or within a building (e.g. in a patio; Fig. 5(b)), water surfaces or fountains (Fig. 5(c)) or ad hoc installations such as buried pipes that are one-third-filled with water to allow air passage (Fig. 5(d)) and moist filters.

3.6. Conventional heating

Passive solar designs might not be sufficient to provide indoor thermal comfort, particularly in regions with extreme climates [7]. Zone 7 corresponds to temperature values between −5 and 1 °C (Fig. 1). In this case, passive strategies are insufficient to achieve a comfort zone in the space and it becomes necessary to use a device that consumes electric energy, gas, oil or coal to increase the mean temperature by 20 °C.

In the winter, a temperature of approximately 20 °C is sufficient to enjoy an appropriate level of comfort, and one must consider that reducing the temperature by one degree represents an energy savings of 8%. In many climates, the heating can be turned off at night because the heat that had accumulated during the day is more than sufficient. If a person is only outside of the home for a few hours, it is convenient to set the thermostat level at 15 °C (or the economical settings of certain devices). If, however, many hours are spent outside of the home, it is convenient to completely turn off the heat.

The optimal location of heating systems such as radiators is below the windows in order to obtain maximum heat radiation; additionally, it is inadvisable to block radiators with furniture in order to best take advantage of the heat (see the example in Fig. 6). The accumulated air in the heating circuit hinders heat transmission, which is why it is advisable to purge radiators when they are first used at the beginning of the season. It is advisable to lower the thermostat temperature or turn off the heat in empty rooms to increase the energy savings.

3.7. Solar protection

This area corresponds to temperature values of 20 °C or higher (zone 8 in Fig. 1). In this case, bioclimatic architecture strategies attempt to avoid heat gains through solar radiation and avoid temperature increases to remain in the comfort zone. Protection is focussed on all building openings but can also be generally applied to the building envelope. Solar protection can be implemented naturally such as the use of trees with deciduous leaves (Fig. 7(a)) or through architectural elements such as pergolas with deciduous vegetation (Fig. 7(b)), porches (Fig. 7(c)), awnings (Fig. 2(a)) and finally interior store (Fig. 7(d)) and exterior (sunblind) blinds (Fig. 7(d)) and exterior slats (Fig. 7(e)). The last resource is used in certain public buildings in very warm areas as an exterior building screen.

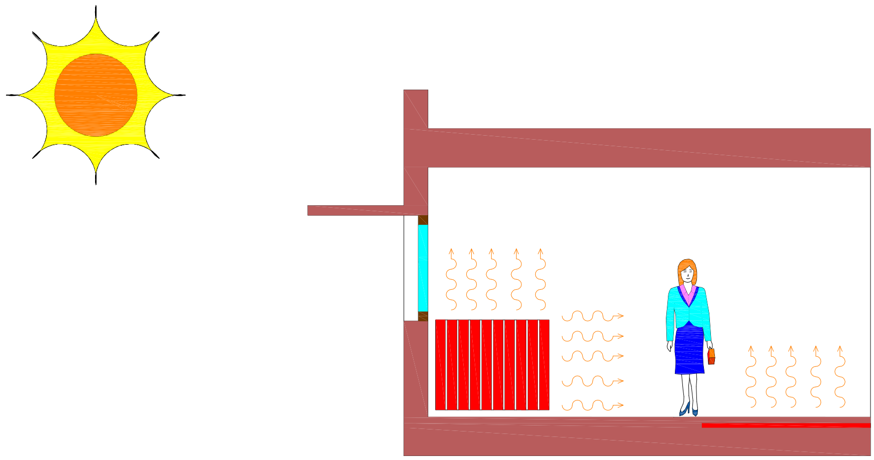

Fig. 6. Example of conventional heating.

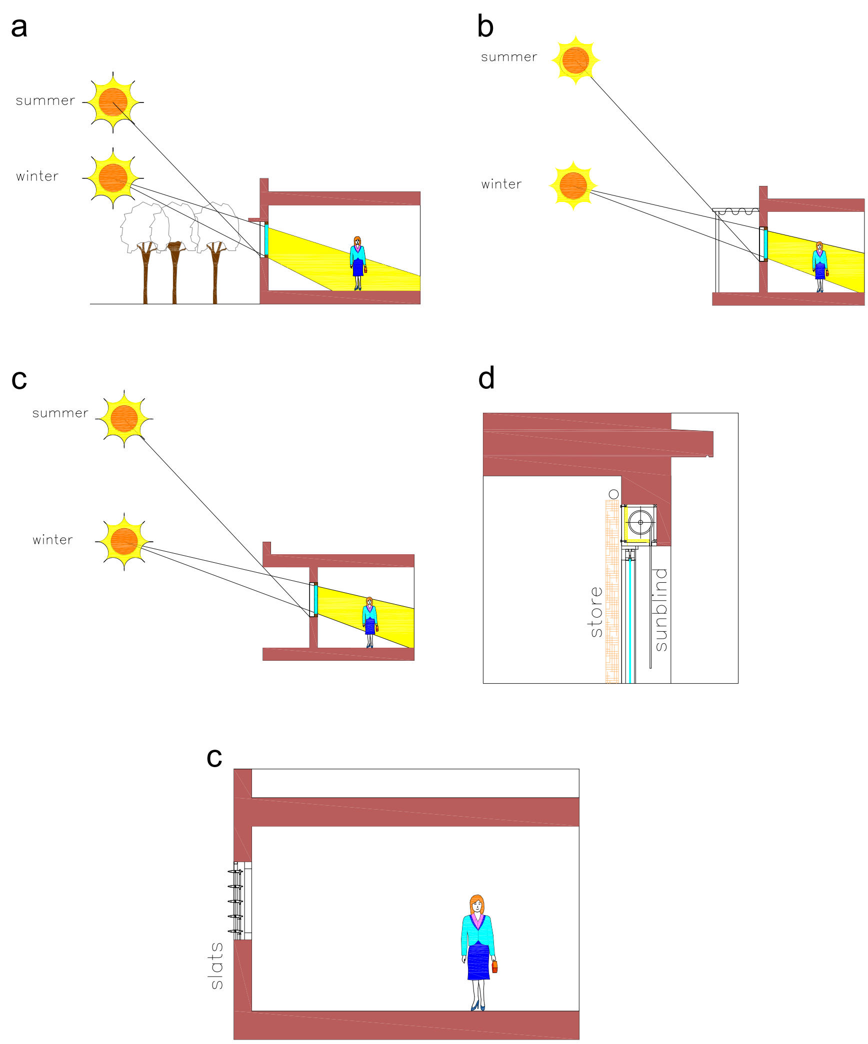

Fig. 7. Solar protection techniques: (a) Solar protection mediated by deciduous vegetation; (b) pergola with deciduous vegetation canopy-mediated solar protection; (c) porch as a solar protection strategy; (d) sunblind (outside) and store (inside); and (e) horizontal slats.

3.8. *Cooling through a high thermal mass*

This strategy corresponds to zone 9 in Fig. 1 and is bound by temperatures between 20 and 35 °C and a dotted line extending from the intersection of 24 °C and 80–50% relative humidity to the intersection of 35 °C and 30% relative humidity. This strategy comprises the thermal mass of the building envelope that receives and subsequently transmits radiation to the interior with a phase difference to achieve climate uniformity throughout the day. Capacitive materials help to create a phase difference in the daily energy transmission and temper the intensity. Nocturnal dissipation by the façade and roof is necessary. It is ideal to place a mobile

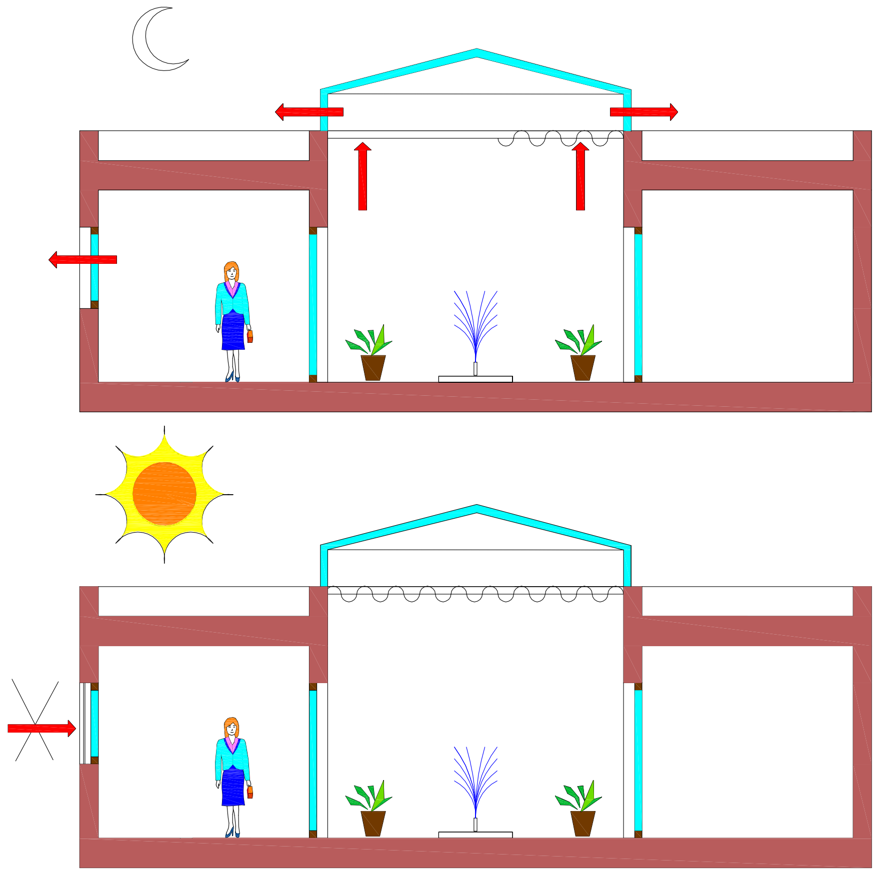

Fig. 8. A Sevilian patio with a protective moving mechanism that avoids heat gains in the daytime and favours nocturnal dissipation.

daytime protection device to avoid gains and favour nocturnal dissipation; an example of this comprises the awnings that cover patios in Seville (Fig. 8). This strategy is very advisable in climates with temperatures that are near comfortable levels.

3.9. Evaporative cooling

This strategy corresponds to zone 10 (Fig. 1) and is bound by temperatures between 20 °C and 40.5 °C and a dotted line that extends from the intersection of 25.5 °C and 75% relative humidity through the intersection at 38.5 °C and 20% relative humidity to a third intersection at 40.5 °C and 10% relative humidity. This strategy is very advisable in dry and arid climates. It aims to achieve comfort by reducing the temperature through water evaporation while simultaneously increasing the relative humidity. Humidification can be achieved using exterior vegetation (Fig. 9(a)), water (ponds or fountains; Fig. 5(c)), buried pipes that are one-third-filled with water (Fig. 5(d)), patios complemented by the presence of water and vegetation that help to reduce the temperature and increase the relative humidity by conducting an evapotranspiration process (Fig. 5(b)), vegetative cover (Fig. 9(b)), the spraying of water on the roof (Fig. 9(c)), the spraying of water indoors to reduce the temperature of the overhead air (Fig. 9(d)), and the production of air circulation through convection.

3.10. Cooling by high thermal mass with nocturnal renovation

This strategy corresponds to zone 11 (Fig. 1) in the Givoni diagram and is bound by temperatures between 20 °C and 44 °C and a dotted that passes from an intersection at 44 °C and 5% relative humidity through another intersection at 31.5 °C and 32% relative humidity to a final intersection at 24 °C and 80% relative humidity. This strategy creates a phase difference between the effect of the daytime and night time outside temperatures to conduct a nocturnal renovation. It is effective when the climate exhibits significant thermal differences between the day and night periods. The building envelope should comprise capacitive materials that transmit energy with the largest phase difference possible (approximately 12 h) with some damping. At night, dissipation and renovation should be conducted through openings, patios and roofs.

3.11. Cooling through natural and mechanical ventilation

This strategy corresponds to zone 12 (Fig. 1) and is bound by temperature values between 20 °C and 31.5 °C, relative humidities between 95% and 20% and a dotted line that extends from an intersection at 31.5 °C and 50% relative humidity to another intersection at 26.5 °C and 95% relative humidity. A greater thermal sensation is achieved while the indoor air is simultaneously cleaned. This can be achieved naturally using cross-ventilation from north to south facades or dominant winds (Fig. 10(a)), the chimney effect (Fig. 10(b)), a solar chamber (Fig. 10(c)), subterranean ventilation (Fig. 10(d)), wind towers (Fig. 10(e)), evaporative towers (Fig. 10(f)), vertical spaces within a building (Fig. 10(g)) or patios (Fig. 10(h)). Additionally, this effect can be achieved mechanically using fans or blowers.

3.12. Air conditioning

This strategy corresponds to zone 13 in Fig. 1 and its objective is to achieve comfort by installing air conditioning machines to reduce the temperature and relative humidity. However, a temperature of 26 °C is sufficient during the summer and does not

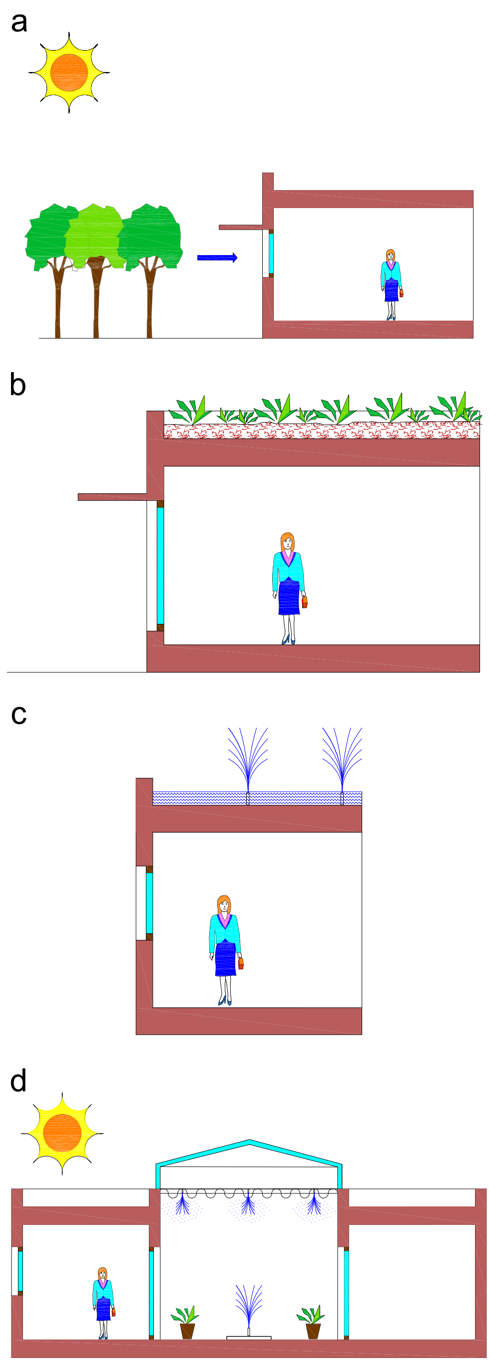

Fig. 9. Evaporative cooling techniques: (a) Exterior vegetation for evaporative cooling; (b) roof vegetation for evaporative cooling; (c) roof watering for evaporative cooling; and (d) interior watering for evaporative cooling.

require the consumption of excess energy. Two additional and very common recommendations regarding air conditioning use include not setting the thermostat at a lower-than-normal temperature, as this leads to energy waste, and turning off air conditioning devices when leaving the home.

3.13. Conventional dehumidification

This is represented as zone 14 in Fig. 1 and corresponds to a zone with a temperature above than 25 °C and a relative humidity above 80%. The objective is to incorporate strategies to absorb water from the environment in order to achieve the comfort zone. This is accomplished using absorbent salts and saline cells and requires complementation with other strategies.

3.14. Air conditioning of the home

When it is not possible to achieve a comfort zone within a building while using only bioclimatic architecture strategies, these natural solutions should be used in addition to mechanical strategies such as air conditioning [41,45]. We dedicate this section to some recommendations and advice regarding the optimisation of energy consumption while air conditioning the home.

We define air conditioning as temperature and humidity control and management inside the home and include both heating attempts in cold climates/seasons as well as cooling attempts in warm climates/seasons. Appropriate thermal insulation of the home will enable the reduction of heat leaks in the winter and the cooling demand in the summer. A home with very well insulated walls and roof and double-paned glass windows will achieve some savings in the energy consumption used for heating and cooling and will also experience reduced sound pollution.

Similarly and in new designs, an optimal building orientation that designs the principle façade with the south orientation and avoids badly insulated windows and walls on the west side of the home will contribute significantly to reductions in energy expenses because allowing the maximum possible solar radiation during the winter permits savings in heating. However, if solar radiation is prevented during the summer, significant savings can be achieved in cooling. Awnings, blinds and curtains permit heat conservation during winter nights and avoid heat entry during the summer. In warm climates, light roof and exterior wall colours reflect the sun, thus preventing the heating and improving the lighting of interior spaces. Additionally, a fan (preferably a roof fan) might be sufficient to maintain adequate comfort levels in these climates.

Proper ventilation can be generally achieved by opening a window for 10 min, during which it is advisable to turn off heating or air conditioning. It is advisable to install thermostats or programmable clocks to regulate the temperatures of the different spaces within the home as functions of their occupation regimes. It is advisable that installed equipment to cool and/or heat the home should be very efficient, and the intended uses of the equipment and the dimensions and characteristics of the spaces to be heated or cooled should also be considered. Similarly, the performance of appropriate maintenance and inspections of air conditioning equipment is recommended to extend the lifespans of these machines and improve the safety of their use.

4. Major trends in bioclimatic architecture

4.1. Adapting the strategies of vernacular architecture for current architecture

Bioclimatic architecture is occasionally based on vernacular architecture and attempts to analyse traditional architecture based on the climate and culture of a place and to study the architectural and construction solutions [46]. Vernacular architecture has experienced a slow evolution during which it has gained social, cultural, religious, economic, technological and climatic knowledge related to particular places to yield quite singular architectural designs [47,12,48,49]. This type of architecture adapts to the climate of the place without using additional devices that consume energy and leave an ecological footprint [22,33,50–68]. Table 1 summarizes some examples of adapting the strategies for vernacular architecture in current architecture; these examples are sorted by year to show the low evolution that has taken on this topic over time.

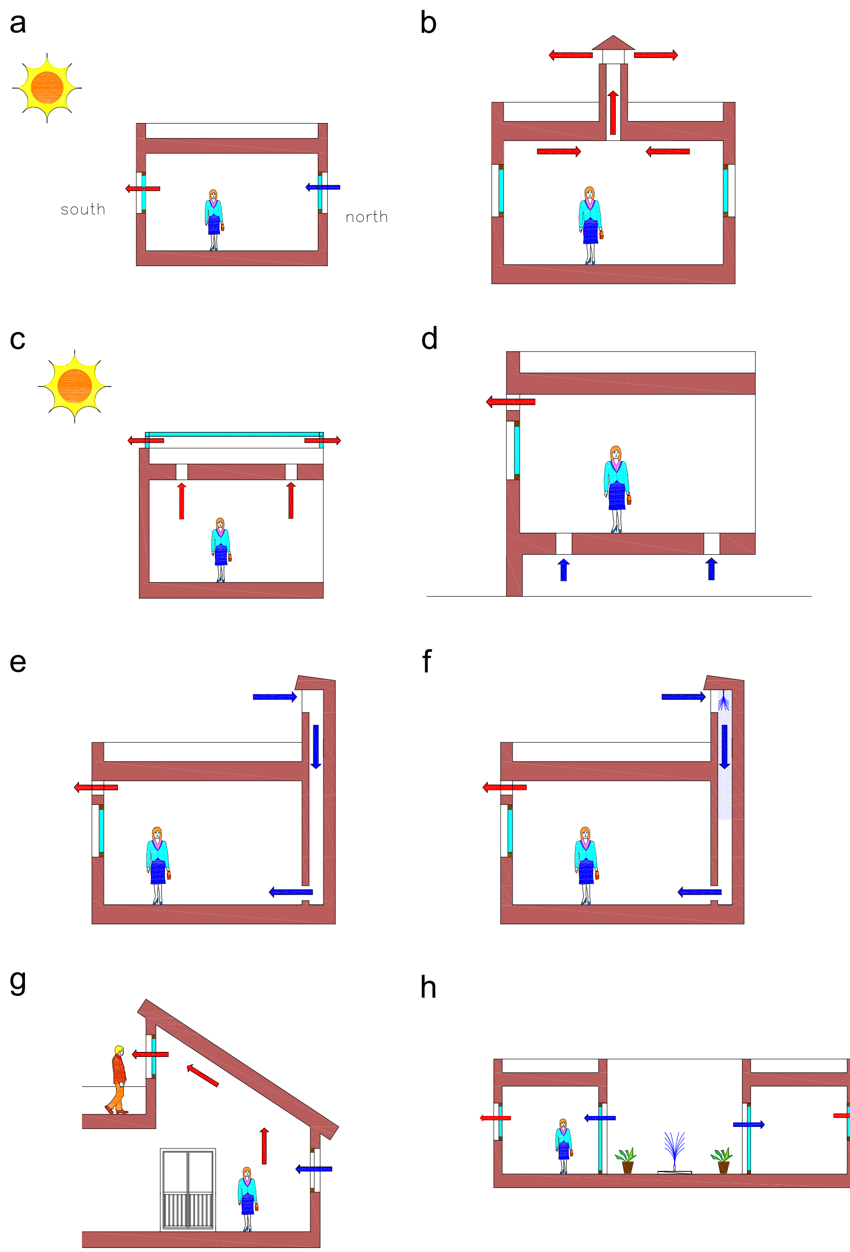

Fig. 10. Natural and mechanical cooling ventilation techniques: (a) Cross-ventilation in a north-south direction; (b) chimney effect; (c) solar chamber; (d) subterranean ventilation; (e) wind tower; (f) evaporative tower; (g) vertical spaces within a building; and (h) patio as a natural ventilation-mediated cooling solution.

Scientific studies of this trend, which implies a re-orientation [69], began in 1977; however, there was little scientific production until the last decade, when such production intensified. The most active countries in this area are India, Greece, Spain and Brazil. The concept of vernacular architecture implies the consideration of certain aspects of construction [70] as follows: (a) traditional construction practices are related to the wisdom of popular knowledge and are passed along via tradition with little or no professional intervention in the construction phases. (b) The materials are particular to the place of construction and the technologies are adapted to the local bioclimatic characteristics. In this sense, local architectural designs will incorporate use of wood or earth as construction materials [71–74]. (c) Its use is mainly related to rural areas where modern construction technology has no reach.

To perform an analysis, the first areas of study are the location climate [13,75,76] as well as the solar radiation and even the predominant wind orientation [16,77], all of which can affect the building envelope. An analysis will also address the materials with which buildings are constructed and the encompassed architectural pieces and their relationships to collect data about the thermal performance and temperature evolution in vernacular architecture [9].

From such an architectural analysis, one might concludes that the design provides general climatic, visual and sensorial comfort [78], helps to control natural lighting, cooking and natural temperature maintenance [79] and, in some places, even provides sustainable tourism [80]. The strategies used are recorded to facilitate later translation to modern architecture or attempts at restoration, rebuilding or improvement [81,82]. The strategies have been proven and tested and therefore their study implies an advancement to acquire architectural comfort with zero energy consumption. The variety of strategies is as broad as is the variety of climates, popular customs and cultures [22,46,49–54,57–60,62,69]. Current architecture is based on climate control devices to maintain comfort within structures. This strategy produces elevated energy consumption that

Table 1
Adapting the strategies of vernacular architecture for current architecture.

Year	Country	Proposal or research aim	Ref.
1981	France	For several projects in Languedoc (France) utilize site and climate to decrease heat losses and optimize direct gains	59
1981	Spain	This project plans to save up to 60% office building energy demand by means of passive techniques and reduce conventional energy consumption to only 10–20% of the usual consumption with active solar devices: solar thermal collectors for heating and cooling and photovoltaic panels for electricity	66
1983	France	The use of sun as natural lighting and energy source is demonstrated in a partly underground single family dwelling. In a mountain climate, a two storey greenhouse will be presented	61
1983	Saudi Arabia	This paper determines the natural resources and bioclimatic roots of the traditional settlements in an important area and suggests a future direction for meaningful architecture in this region	67
1985	Iraq	Roofs of such souqs that exist in Iraq have both fallen and disappeared completely or been replaced by inappropriate shabby materials like corrugated iron. In order to conserve the novel concept of the souq, the study is a bioclimatic approach to the provision or a comfortable environment both in summer and winter	52
1985	Italy	They present the evolution or the bioclimatic architecture according to a specific cultural and climatic context to propose a framework for the future orientation	53
1994	Iran	She focuses the research in the “wind towers” in Iran, country with a desert climate (torrid heat during the day, cold at night)	54
1994	Italy/Europe	Analyze the passive architecture of the different countries of Europe. They give a prospective on the practice of building solar design in the Europe	55
1994	Mediterranean countries	Present situation and trends in heating and cooling are discussed, as well as the use of solar energy for hot water production. Also the relationship between the mediterranean climatic context and the potential of bioclimatic architecture is examined	68
1994	Belgium	The main purposes to be pursued in the climatic conception of commercial buildings are to reduce heat loads, to allow good exploitation of natural light and ventilation in order to be able to avoid or reduce the use of air-conditioning	74
1996	Italy	The highlight that Knowing and utilising natural sources of heating and cooling, the elements of microclimate, of vegetation, of natural convection of air, the heat insulation or storage properties of materials, is just as essential for a correct design as being able to use shapes and materials correctly to ensure structural stability, to withstand the effects of earthquakes, or to design spaces which are functional to their intended uses, in addition to being pleasant to the eye	51
1998	UK	It is highlighted how bioclimatic architecture represents the use of materials and constructive elements under sustainability criteria. It represents the optimum-energy generation concept by means of the active or passive accumulation	58
2001	Nigeria	This paper examines and analyses the climate of Nigeria with respect to building design parameters: temperature, relative humidity, air velocity and solar radiation, with a view to providing design recommendations for the achievement of physiological comfort	65
2004	Spain	They made a review of bioclimatic strategies in the Spanish popular constructions. The aim is to translate some of the bioclimatic strategies used in vernacular constructions to the present ones	20
2005	Mexico	A case study is presented in which a rammed earth settlement built in this industrial era by a Mexican community was proved to provide healthy, thermal comfort and social agreeability to users. The need for rehabilitating old constructions in rammed earth follows the results of this study which had focussed on the high levels of well being in indoor spaces built with local clay and traditional techniques	71
2006	Egypt	This paper aims to consider the ancient Egyptian approach to sustainable urban design and rehabilitation	45
2006	Iraq	They analyze the old builders from this region, as shows that they putted a big effort to create passive bioclimatic houses that corresponds the negative effects Basrah's macroclimate	46
2006	Italy	They classify and make a critical analysis in recent sustainable buildings for the Italian alpine region in order to verify the congruence of new typologies and new materials with the local culture and tradition	56
2006	Mexico	Analyze the bioclimatic behaviour of traditional architecture for future constructions in Tecozautla (Mexico), located in a hot dry climate where an important number of traditional and historical houses still exist	57
2006	Egypt	They analyze the main characters of the traditional architecture in the old settlements (Balat, Al Qasr), pointing out both the typological and the technological aspects (local materials and construction processes), focussing on their environmental sustainability (presence of bioclimatic features, integration into the landscape, minimum waste of resources)	
		The appreciation and successful protection of the vernacular heritage depend on the involvement and support of the community, continuing use and main tenancy	63
2006	Brasil	The purpose is showing the contribution to the development of a less aggressive architecture, more attentive and integrated to the environment. It presents the architectonic solutions used to adapt his buildings to the hot and humid weather of the Amazonian region, by the study of two of his main works, where the use of timber was aesthetic and structurally explored	70
2007	Bulgaria	The involvement of the ancient Bulgarian houses in the surroundings and their composition reveal nearly all aspects of Solar Energy and energy efficiency tools application: direct/indirect gains, thermal mass, convectional loops, sun spaces (atrium case), solar chimney, and synthesis exterior/interior	62
2009	Algeria	Hey make a comparative analysis between the existing traditional and typical modern housing. Modern house seems inappropriate for a desert climate. Traditional houses are most effective in answering the heat problem in summer	48
2009	Greece	This study investigated the luminous and thermal environments in a chosen building (well-preserved mansion in the Vysitsa village), which was designed and constructed, based on accumulated knowledge and past experiences to provide environmental delight to the occupants	64
2009	Cuba	This study makes field measurements for a comfort survey at residential buildings in Old Havana. Based on the historical overview, the measurements and the survey, some preliminary design recommendations for residential buildings in Old Havana are provided	76
2009	Canada	This paper suggests that the integration of passive bioclimatic strategies can provide an intensive sensory and mental pleasure while optimizing both the buildings' and the occupants' performances	77
2010	India	They identified many house typologies in a vernacular settlement (Marikal). This study calls for a code of practice balancing modernization with the vernacular	47
2011	Greece	Characterize this architecture for integrating in the refurbishment of existing buildings or the design of new ones in traditional surroundings	49
2011	India	solar passive features related to building form and orientation, envelope design, shading, use of natural ventilation, internal space arrangements and activities of the habitants are explained for all the climatic zone of the region (North-Eastern India)	50
2011	Argentina	The aim is to offer a brief description of the most significant architectural types Cuyo Region (Argentina), providing examples of buildings, which are still preserved, within a frame of analysis of the social-historical and technological situations in which these buildings were erected	69
2011	Mexico	This paper exposes some of the main features that involve rammed earth architecture, with the purpose of contributing to its promotion, conservation, and re-development. Earthen architecture, when compared with other modern building methods and techniques, has outstanding qualities from a sustainable point of view	72
2011	Spain	This paper draws attention to the significant diversity among the typologies of rammed earth buildings constructed in Spain in recent years. They highlight that Rammed earth could have a promising future	73

Table 1 (*continued*)

Year	Country	Proposal or research aim	Ref.
2011	Iran	The research results show that in Esfahan city, we could provide thermal comfort with observance of authentic principles of architecture and using natural energy resources	75

affects the environment. Vernacular architectural strategies help reduce energy consumption and also represent the basis from which to develop other strategies for better adaptation to the social conditions of modern architecture.

These strategies are linked to specific conditions; however, it is interesting to note that these can be exported, as in the example of the patio from Mediterranean architecture that has also been used on the American continent. Therefore, given the global nature, it is interesting to attempt strategies from other places in order to reach similar objectives. In summary, the analysis of vernacular architecture is fundamental to understanding the climatic behaviour of a building in its environment, the knowledge of which has been accumulated for centuries, and to adaptations of this knowledge to current societal customs.

4.2. *Experimentation of bioclimatic architecture in construction*

This trend comprises translating the knowledge of bioclimatic architecture into construction projects for new buildings, rehabilitation projects or construction on existing structures. Table 2 summarizes some examples of experimentation of bioclimatic architecture in construction; these examples are sorted by year to show little evolution that has taken on this topic over time. Italy, Spain and Brazil are the countries that have most adopted this trend, and the most frequently used strategies are solar spaces, Trombe walls, solar chimneys and direct gaining systems [83].

Each area has incorporated strategies that fit their respective climates in order to achieve comfort. In some cases, the materials and architectural elements that comprise a strategy were studied previously by conducting simulations and even formulating fairly significant savings estimates in some cases; for example, 50% cooling and 23% heating [84] savings were estimated for insulation and atrium spaces that would capture/dissipate heat energy. A benefit analysis of bioclimatic construction is performed once the structure has been completed [61,85–89]. The most traditional strategies include the use of reflective materials to cover surfaces [90], which reduces the demand for cooling energy, the use of nearby vegetation to provide humidity, and the presence of ponds [91], passive cooling [92–94] and passive ventilation [95].

Existing construction can also be rehabilitated by reinterpretation or rebuilding while always interpreting the initial comfort strategies of the existing building or the methods of comfort provision at the time of construction in order to restore the comfort level through a more updated approach [96,97]. Occasionally, projects intervene in existing buildings through significant bioclimatic improvements [10,98–106]. The rebuilding of old structures involves an awareness of the initial strategies used to generate the initial design, which can then be translated to other structures; this occurred with the Sassi di Matera hypogea in Italy [107], which exhibits the thermal benefits of underground buildings, specifically the significant thermal inertia that allows the occupants to experience year-round thermal comfort and has prompted tests of buildings with rammed earth walls in Spain [74] and Mexico [72,73].

In China, the use of the solar chimney in homes has assisted not only with climatic comfort due to the increased ventilation but also with reducing the amounts of interior pollutants; the latter is further promoted by the presence of surrounding outdoor vegetation, which also helps to reduce the outdoor pollution levels [1]. Elements such as the wind catchers used in Nagapattiam (India) help to reduce the interior temperature by up to 10 °C (from 26 °C to 16 °C) at exterior temperatures of 40 °C and modulate the interior relative humidity by reducing the peak level from 95% to 75% [108]. Wind catchers are also one of the vernacular architecture elements in warm areas of Iran and are very frequently used in central and southern part of this country [109,110]

The use of rooftop water tanks for passive cooling through nocturnal convection cooling is a model taken from Greek coastal areas [111] and allows the reduction of cooling loads by 87%. Universal expositions are an excellent venue in which to promote and disseminate the benefits of this architecture. Some examples included the Spanish booth at the Expo-Zaragoza event [112] and the Belgian booth in the Expo'92 in Seville (Spain) [113]. The method used for the exterior spaces in the Expo'92 in Seville was also implemented in Maracaibo (Venezuela) [114].

4.3. *Application of innovative strategies to bioclimatic architecture*

This trend attempts to translate innovative bioclimatic strategies. Worldwide, the countries in which the highest numbers of test cases have been attempted are Italy, Brazil, Greece, USA and Spain. Most of the tests intended to achieve energy savings by using bioclimatic guidelines during design [115]. The majority of the strategies were adapted from vernacular architecture; others were “ex novo” and used parameters extracted from previous studies such as the use of the southern exposure coefficient (Cfs) [116], as southern exposure is very important for solar gains during the winter [117]. Until recently, the shape coefficient Cf (the lesser the envelope surface area relative to the building volume, the lower the energy demand) was used. Adding the Cfs introduces the concept of addressing the amounts of the façade and volume with south-facing orientations.

An architectural space element such as a glassed-in gallery was found to store energy and reduce heating loads by 15 to 32% on clear days in Northern Spain [118].

Among the more modern strategies, we can highlight the integration of thin BIPV photovoltaic films on buildings [119], green roofs to buffer excessive radiation, the spraying of water on roofs [120], the placement of pipes buried 0.5 to 1.5 m deep to provide cooler air during the summer and warmer air during the winter [121], the use of solar chimneys to promote the renewal of outside fresh and clean air [1], the use of a glassed-in gallery to provide as much as 15 to 32% of the required thermal energy on clear days [118] and a double-layered building envelope to temper the interior environment [122].

These strategies are valid for both conventional buildings and very tall structures, which require a separate set of bioclimatic strategies [123,124] for ventilation and lighting [125,126]. The strong influence of solar radiation has also been studied, as has the influence of vertical gardens (vertical landscaping) [127], courtyard design and the use of voids within the building to provide adequate natural ventilation to eliminate pollutants and maintain climate control. Similarly, ultrasonic spray nozzles have been used to introduce humidity and produce evaporative cooling [128].

Table 2
Experimentation of bioclimatic architecture in construction.

Year	Country	Proposal or research aim	Ref.
1983	Italy	The realization of 44 bioclimatic dwelling units at Rignano sull'Ar-no, Florence, is described here. The work has the outlines of an emerging solar architecture, conceived according to the will of the client - Coop. "Helios 78" - to build multifamily residences and facilities, with modern distribution scheme and with low cost of management, by using renewable energy systems	90
1984	USA	Passive cooling activities and their documentation from the last decade are reviewed and evaluated from the perspective of the U.S.A.	93
1985	Australia	The climate of Australia is presented, with bioclimatic analyses for the six major zones. The socio-economic background is outlined. The built environment is discussed through an historical sketch and pointing out a few major trends in current practice	99
1985	Brazil	This work presents an analysis of the climate of different regions of Brazil, their vernacular and historical buildings and the contemporary architecture, searching for the possibilities of bioclimatic architecture in this country	87
1997	Israel	The article describes a 'climatically adaptive' approach to intelligent building in which a variety of technologies are integrated in the architectural design to provide thermal comfort with a minimal expenditure of energy	104
1997	Italy	This paper presents the analytical description of the rehabilitation procedure of an urban area which includes a large number of completely abandoned, historical industrial buildings, located in Legnano (Italy)	97
1998	International	An international survey of contemporary architecture built according to bioclimatic, or green guidelines. Examines 50 buildings constructed in the past years, explaining how they respond to the need to achieve harmony with their settings, conserve energy, and provide for the health and well-being of their occupants	60
1998	Italy	Study for the areas of the high speed rail station in Florence (Italy) is presented at the synthesis of a comprehensive strategic design of the overall objectives bring out by the town-planning scheme of the city	84
1998	Italy	The experience of Studio Nicoletti in low energy building is exemplified by five groups of designs based on different typologies	89
2002	Venezuela	The main purpose of this paper is to determine, for hot and humid climates, in which proportion the exterior spaces energy flows intervene in the human thermal comfort	115
2005	France	Impact of building design on the performance of a solar desiccant cooling system	94
2005	Mexico	The paper deals with the environmental characters of rammed earth constructions, from the points of view of both eco-sustainability and human health. A case study is presented in which a rammed earth settlement built in this industrial era by a Mexican community was proved to provide healthy, thermal comfort and social agreeability to users	73
2006	Colombia	The presented case study relates to a naturally ventilated complex commercial building located in Colombia. The goals of this project are: a balanced integration between architectural features, bioclimatic requirements, cost-benefice relations and constructive needs	102
2006	Spain	This paper details the construction of five Research and Demonstration Building Prototypes (RDBP) in different Spanish climatic zones. One of these prototype buildings at the Plataforma Solar of Almeria (PSA), located in the Tabernas Desert was analyzed	88
2007	Canada	This project proposes an illustration of an integrated approach to the study of the luminous and thermal environments in the design process for the new extension of an educational building at Laval University, in Canada	101
2007	Venezuela	The main objective of this paper is to present and discus estimated SPEEI energy efficiency results as an Indirect Evaporative cooling technique suitable to use in a tropical climate	95
2008	Brazil	This paper aims to present the results of a sustainable architectural project in an urban area, developed in a participative process	100
2008	International	Photometric analyses were carried out the measure the optical properties of a sustainable light coloured cool paint. Dynamic energy simulations were run for different Mediterranean localities (Rome, Palermo, Seville, Athens, Tripoli), buildings geometry (stand alone and row house), different thermo-physical properties of the opaque envelope (solar reflectance, U-value, thermal capacity) and of the whole building (natural ventilation rates and shading of glazing systems)	91
2008	Spain	The subject of this article is to describe the technical installations in the Spanish Pavilion for the International Exhibition "Water and sustainable development" in Saragossa 2008	113
2009	Greece	The focus of this paper is on passive cooling strategies raising the question of the need for and dependence on mechanical air conditioning in seaside resorts on Greek islands	112
2009	Italy	In this study, the authors analyze the energy and microclimatic performance of hypogeous structures in three states: not-restored, immediately after restoration, and a few years after restoration (in normal use)	108
2009	USA	This paper presents the results from a series of experiments on the uses of several less well studied elements of the landscape in the cooling of buildings; vines, landscape ponds and vegetated roofs	92
2010	Spain	Study about the rehabilitation-revitalization of some old headquarters, situated in Gardeny area in the city of Lerida, consisted of the intervention in three existing buildings and there restructuring in investigation spaces for the university and the food and agriculture business	85
2011	Bahrain	This paper is a theoretical application of the urban climatic values of Bahrain to the determination of Bioclimatic Design Strategies to be considered in the architectural design	86
2011	India	The authors have conducted the qualitative and quantitative analysis to investigate the indoor environmental condition of a vernacular residential building in coastal region of Nagapatinam	109
2011	Iran	The authors introduce Iranian ventilation structures called Badgirs for air conditioning	110
2011	Israel	In this paper, the authors present the fundamental ideas, logic and thoughts that led to the definition of the requirements for an energy efficient building that warrants green points according to the Israeli Green Building Standard	103
2011	Mexico	This paper exposes some of the main features that involve rammed earth architecture, with the purpose of contributing to its promotion, conservation, and re-development. The text is centred mainly on the characterization of the traditional way of executing this building technique in México	74
2011	Mexico	The authors evaluate strategies and actions that lead teaching, research, culture divulgation and campus management towards a more sustainable culture	105
2011	Poland	The paper present strategies for climatic and sustainable design for education of young architects	106
2011	Spain	This paper draws attention to the significant diversity among the typologies of rammed earth buildings constructed in Spain in recent years	75
2011	Turkey	This paper aims to detect some clues about the outline of the residential architecture within the context of cultural sustainability in Bodrum in the light of residential architecture samples	107
2012	China	This study describes the work on the development of climatic applicability maps of downdraught cooling in China based on three related climatic characteristics: cooling degree hours, dry bulb temperature-wet bulb temperature and 26 °C-wet bulb temperature	96
2014	Iran	This paper reviews the traditional architecture and history of wind catchers in Iran along with its performance	111

4.4. Promotion of bioclimatic architecture

Countless scientific studies have unmasked efforts to promote bioclimatic architecture in the absence of the same, particularly to correct the influences of other structures on the surrounding exterior environment [51,129]. Some efforts attempt to contrast economic opulence, including the use of air conditioning, concrete, glass and marble, with the intent of realignment with the values of traditional communities [69]. The most active countries with respect to this trend are Argentina, Brazil and Italy. Solar energy is inexhaustible, and methods for its capture via appropriate building strategies comprise a current and recurring subject [68,130–133].

The majority of studies address populations with scarce economic resources with the intent to promote bioclimatic values using local materials and techniques [19,46,134] and maintaining tried and tested cultural aspects and strategies [95] such as the use of patios as buffering elements in difficult climates [16,135], the use of air capture within patios [108] and the use of walled gardens in desert climates [136]. Other studies have addressed fundamental architectural structures in order to adapt to the exterior climate and modulate the interior areas [137]. Countless attempts have been made to create eco-villages in which bioclimatic strategies would be practiced in addition to a more far-reaching vision focussed on living in harmony with the environment [138] or the construction of homes for farmers in rural Africa [139].

Climatic comfort is a very important factor in improving people's wellbeing, particularly that of employees in the workplace as a strong driver of increased productivity [140]. Industrial construction is also a focus of such strategies [141]. Examples include iconic buildings such as author warehouses [142], heritage rehabilitation [143,144] in both urban settings and dispersed habitats, commercial buildings that achieve lighting savings and avoid overheating [75], libraries with special roofs with which to study performance [145], university and educational buildings [121,146,147] and hospitals, where studies of climatic comfort achievement focus on avoiding the use of additional devices that consume energy and leave ecological footprints [148].

4.5. Bioclimatic architecture in urban planning

A focus has been placed on integrating urbanism to the climate [149,150] by analysing the thermal sensations of people in public spaces and the thermal differences between rural and urban environments [151,152]. All research related to this trend has been directed towards analysing and adapting the environments near buildings, as these are also urban spaces and fundamental for human habitat. Such research can subsequently facilitate the formulation of guidelines to follow during future urban planning. Thus, bioclimatic architecture could begin with bioclimatic urbanism, including tracing streets with intentional solar orientations and locating free garden spaces to create settings that favour comfort in public spaces that will be facilitated not only by architectural elements but also by deciduous vegetation elements.

Urban geometry incorporates ancient street plans that have yielded positive results and studies compact European cities as well as Mediterranean cities to subsequently create guidelines for ecologically and culturally richer cities. The strategic locations of vegetation in urban spaces are studied to create integrated landscapes such as those observed in the cities of ancient Egypt [47]. The interaction of vernacular construction with urban interstitial spaces is fundamental to forming a unit that results from the local, cultural, social and religious values, bioclimatic elements and natural resources. Bioclimatic guidelines can also be directed towards the treatment of urban elements in exterior spaces such as courtyards [21], as the use of vegetation and water in these spaces as well as of construction materials with high thermal inertias and appropriate reflectivity values will significantly reduce the climatic indices. The city is therefore viewed as a succession of empty spaces that provoke landscape enriched by the personal and private experiences of its inhabitants [153].

The analysis of urban-level environmental variables is fundamental to action. In Varsovia [117], an analysis of the temperatures, relative humidities and wind speeds in various structural urban areas such as parks, forests of different sizes, different types of homes, industrial areas and open areas both within and outside of the city was conducted to encompass all of these data for urban development.

The presence of vegetation is fundamental in arid areas because it helps to improve the temperature and relative humidity conditions, leading to increased human wellbeing. In addition, shade provides solar protection. Related policies have focussed on planting specified vegetative masses in existing areas and increasing the numbers of new areas [154]. The reduction in climatic difficulties in public spaces using specific techniques such as passive cooling has been proven [21].

In certain climates, emphasis has been placed on protecting homes in rural areas from wind action using forests, low forests or wind-breaking hedges (or a combination of these strategies) [155]. In addition to mitigating the effects of wind action, the vegetative masses interact with the climates nearest the buildings to modify the temperature and humidity conditions. In addition, vegetation can be integrated with construction to offer more ecological landscapes. Urban landscapes that possess vegetation and water have improved temperature conditions and favour clean air, according to an urban climatological point of view [156]. Urban planning should consider the cohabitation of daily human life with aesthetic aspects [157].

Urban plans with bioclimatic guidelines have been implemented and have regarded both organisation and aspects affecting the designs of the buildings being organised [83,158]. The use of sensible landscaping or bioclimatic urbanism is being implemented in urban environments such as cities in the Arab Emirates along with other bioclimatic strategies for buildings that act together and are considered as a whole [159]. In summary, sustainability is a broad concept that encompasses the environmental habits of users as well as the architecture and urban design [20]. Therefore, water cycle management within and around buildings can also be a focus of bioclimatic architecture [160].

Renovations with bioclimatic guidelines of the Lleida corporate park in northern Spain will facilitate considerable energy savings for both heating and cooling (this demand represents 40–60% of the total energy demand). A 15% savings in the energy demand have been estimated simply by placing horizontal slats in the windows for solar control and envelope crystallisation. This estimate could increase to 47% when interstitial spaces such as greenhouse spaces that modulate variables that affect comfort and devices that control shading and solar exposure such as vegetation and water sprayers are used [84].

4.6. Inclusion of bioclimatic lessons in study plans

Bioclimatic guidelines have never completely disappeared and some architects have always included these types of strategies in their work, including the lessons by James Rose [161], the “summer house” by Alvar Aalto [162], the incorporation of Mediterranean architecture by Luis Barragán [163,164], the organic architecture of Ken Yeang [165,166] and the passive strategies for tall buildings by Bawa [167]. Eileen Gray's work has been considered a precursor of bioclimatic architecture, as it addressed solar trajectories, wall and roof thicknesses and solar protectors [168]. Currently, the SANA'A team of architects executes projects with many bioclimatic solutions [169].

However, bioclimatic architecture integration has proliferated in architectural study plans during the last two decades. Initially, bioclimatic architecture appeared as an elective course or graduate program or in courses for architects and the training of researchers, specialists and professors but has subsequently become integrated directly into the structures of study plans [18,54,170–178]. Within these study plans, bioclimatic architecture is presented at three levels [171]: the first level, in which the student must obtain and learn all of the relevant climate variables; the second level, which addresses the techniques and concepts of bioclimatic design by applying them to a project in order to properly assimilate this knowledge; and a third level, which includes the urban scale or bioclimatic urbanism. All of the levels initially address the climatic variables of the countries where they are located by progressing from the general climate to the local climate and finally the climate near the building; the student will attempt to bring this building climate as close as possible to human comfort levels using bioclimatic strategies. Some of the principal topics in these study plans include solar geometry, thermophysical material properties of materials, bioclimatic design-related natural principles and laws, bioclimatic strategies and systems and techniques associated with specific strategies according to the climate of the location [179]. Given the holistic character of bioclimatic architecture, it is important to integrate various disciplines to facilitate the development of innovative strategies [164,180,181]. Any construction activity bears an ecological footprint; for this reason, it is important that future architects consider the concept of environmental restitution. To that end, bioclimatic architecture is included in architectural education.

4.7. Technological energy saving developments to support bioclimatic architecture

This scientific trend attempts to create tools that can record microclimate data and analyse any aspects of thermal behaviour in a building interior [182,183]. These developments encompass cell-based designs to incorporate data from habitable interior spaces [184,185], propose climatic classifications based on psychrometric chart [186] or use the bioclimatic data from a location and its influence on human beings to formulate future urban plans [187].

Other authors in the field of automation focussed on analysing energy expenditures associated with heating, cooling, ventilation and artificial lighting in a building. These tools permit a more energetic analysis of buildings that are already constructed or projected in order to adopt more appropriate bioclimatic strategies [188] and include analyses of the airflow through habitable spaces, which represents pressure decreases and mixture effects, or of the airflow in Trombe walls, solar chimneys and similar design strategies [189]. Other research has focussed on optimising control devices in windows to control of solar radiation [190].

Energy savings acquire a greater relevance when usage policies begin to play roles in regulating demand limitations and favouring and incentivising savings through increased energy certifications [2,9,191]. In certain places where the climate does not exhibit excessively high temperatures but does exhibit high relative humidity levels, electricity demand peaks occur when users turn on air conditioning devices, thus triggering phase differences in the electric grids due to the high levels of unexpected demand. This phenomenon can be studied to identify potential corrective measures through the uses of more appropriate architecture, usage strategies and, especially, corrections in user habits [192–195]. User responses are important with regard to understanding their needs related to thermal, lighting, acoustic and olfactory comfort as well as their energy demands for regulating those comfort levels [196].

5. Conslusions

This paper has reviewed the development of bioclimatic architectural strategies. The necessity of bioclimatic strategies for energy expenditure minimisation and the dependence of the achieved energy savings on the severity of the climate in which the building is located have been observed. These principles can be applied in any part of the world, assuming that the same strategy can work in a different area with a similar exterior climate. Additionally, this paper has demonstrated how vernacular architecture represents a development basis for the strategies to be applied; therefore, its study should be emphasised more strongly.

Any research in this area should consider all agents that play roles in the process of architectural construction and the associated facilities. Therefore, actual architectural projects should attempt to reduce the energy demand as much as possible as a function of the climate associated with the building location. However, it is necessary to place a greater importance on climatic comfort as a fundamental architectural objective and to achieve this objective without the assistance of devices that consume electricity and bear large ecological footprints. Knowledge about bioclimatic architecture should permeate all societies as the primary users of buildings that must provide an appropriate comfort zone, thus leading to the minimisation of the use of cooling and heating devices. To this end, societies must become more aware of the environmental impacts of energy consumption and the repercussions for climate change. Additionally, societies must therefore continue to introduce energy consumption reduction policies such as those that are already being implemented in many countries to establish future energy use objectives for buildings. We can therefore conclude that bioclimatic architecture will play an increasingly important role in sustainable development.

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