Design and performance verification methods for naturally ventilated buildings from the experience of ABC 21 EU Project

Izabella Milto[*1,4], Silvia Erba[1], Andrea Sangalli[1], Guilherme Carrilho da Graça[2], François Garde[3], Lorenzo Pagliano[1]

1 Polytechnic University of Milan
Via Edoardo Bonardi 3
Milan, Italy

2 University of Lisbon
Campo Grande 1749-016
Lisbon, Portugal

3 University of La Réunion
40 Avenue de Soweto
Saint Pierre, Réunion, France

4 IUSS School for Advanced Studies
Piazza della Vittoria 15
Pavia, Italy

**Corresponding author: izabella.milto@iusspavia.it*

Presenting author: underlined First & Last name

ABSTRACT

The research exposes a critical feedback loop: the building sector's high energy consumption and emissions contribute significantly to climate change. Warming temperatures, in turn, lead to increased reliance on energy-intensive HVAC systems, further exacerbating the problem.

To investigate the potential of passive cooling systems for achieving energy-efficient buildings, the research proposes a methodology for building design and building performance evaluation. Focusing on the interplay between climate, building design, and urban planning, the research plans weather data analysis, measurement campaigns, and structures the design process into four phases favoring advanced natural ventilation.

The design methodology involves:

1. Identifying optimal cooling strategies based on local climate and building typology.

2. Developing a natural ventilation system, potentially supplemented with strategies to increase the ventilative cooling capacity.

3. Optimizing the ventilation solution.

4. Conducting detailed simulations for thermal comfort and energy use.

Additionally, a survey tool applicable to various case studies has been developed. The tool evaluates the feasibility and extent of natural ventilation use and determines the need for mechanical assistance (fans or passive methods) in driving the air flow.

Key findings reveal that while solely relying on natural ventilation might be challenging in hot and humid climates during rainy seasons, prioritizing passive cooling systems remains crucial. The study demonstrates that mechanically assisted natural ventilation can provide sufficient thermal comfort in many cases. Furthermore, strategies like Nocturnal Ventilative Cooling, coupled with a bioclimatic design approach during the planning phase, can significantly reduce the energy demand of HVAC systems.

By highlighting the potential of passive cooling systems for energy-efficient buildings, this research offers valuable insights for architects and urban planners seeking to create sustainable built environments. It underscores the importance of sustainable practices within building design and offers practical strategies for implementation.

KEYWORDS

Natural ventilation, passive cooling systems, bioclimatic architecture, indoor thermal comfort, energy need for heating and cooling

1 INTRODUCTION

Global and regional climate change increases the temperature of cities and skyrockets the cooling energy use of buildings. The use of conventional compression cycle air conditioning increases the peak electricity demand and obliges utilities to build additional power plants that operate for a limited number of hours per year increasing the cost of the electricity supply [45].

Furthermore, air conditioning can be an important source of environmental and indoor air quality problems, like the ozone depletion and the potential warming of the ambient environment [47]. The considerable operational cost of air conditioning is a serious burden for low-income population that is living in non-thermally protected buildings, with the associated high energy needs for cooling [48].

Due to financial constraints, low-income population is exposed to extreme indoor temperatures highly exceeding the health and comfort thresholds [46]. Without strong and effective policies, the building sector's energy consumption is projected to rise significantly due to climate change combined with several technological, economic and social drivers [1]. During the recent years, several passive and active alternative cooling technologies and strategies for buildings and open spaces have been developed and successfully tested [16].

2 THERMAL COMFORT IN HOT CLIMATES

Thermal comfort is defined as: 'that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation' [58]. It is the parameter of indoor environmental quality (IEQ) which has been more widely investigated and extensive documentation is available in literature [11, 42, 44]. To evaluate the indoor thermal comfort conditions, many surveys about thermal sensations have been the base for the development of various comfort models aiming at predicting the average comfort perception of groups of people exposed to a certain environment.

The assessment of thermal comfort presented in the Standards EN 16798-1:2019 [56] and ASHRAE 55:2020 [58] indicates two main typologies of comfort model:

- the "Fanger (PMV/PPD) model" (EN ISO 7730 [27]), proposed for actively conditioned buildings,

- while the "Adaptive Model" is proposed for naturally conditioned spaces and when active systems, even if installed, are not in use (ASHRAE 55:2020).

In tropical climates and naturally conditioned spaces, field studies have found that the international standard for indoor climate, ISO 7730 [27] based on Fanger's predicted mean vote equations, does not adequately describe comfortable conditions [9,14,37]. In warm climate conditions, PMV predicts that people will feel hotter than they actually do and therefore tends to encourage the use of more air conditioning than necessary. Fanger himself did recognize that "in non-air-conditioned buildings in warm climates, occupants may sense the warmth as being less severe than the PMV predicts" [40].

In the last decades, several design activities and successful construction activities have taken place based on the Givoni's comfort zone [16,21] or the Standard Effective Temperature (SET*) model developed by Gagge [17,18,24] and growing evidence of comfort acceptance by occupants of those buildings has been found [30,31]. Studies and tools are available in literature to compare different thermal comfort models (e.g. Attia et al. [1] developed an analysis application for bioclimatic design strategies in hot humid climates and showed the comfort models comparison for the two major cities of Madagascar, situated off the southeast coast of Africa).

We include in this chapter a review of the recent updates and changes in the international standards. The summary is meant to facilitate practical application of the knowledge gathered in the last decade. The recent updates of the standard have relevant implications for the design and assessment of bioclimatic and passive strategies.

2.1 The Adaptive Comfort Model

The adaptive comfort theory has been developed from field studies and considers the building occupants as active agents interacting with their built environment [11]. This model relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters. There are currently two main standards related to indoor thermal comfort assessment which propose the adaptive model in buildings without mechanical cooling or heating systems in operation: the European EN 16798-1 [56] and the American ASHRAE 55 [58].

2.2 The Elevated Air Speed Comfort Zone Method

According to the standard ASHRAE 55:2020, the Elevated Air Speed Comfort Zone method uses the Analytical Comfort Zone Method combined with the Standard Effective Temperature (SET). It is permissible to apply the method to all spaces within the scope of the ASHRAE 55:2020 standard where the occupants have activity levels that result in average metabolic rates between 1.0 and 2.0 met, clothing insulation I_{cl} between 0.0 and 1.5 clo, and average air speeds V_a greater than 0.20 m/s.

Figure 1 represents two cases (0.5 and 1.0 clo) of the Elevated Air Speed Comfort Zone Method, and it is applicable as a method of compliance for the conditions specified in the figure. The figure also defines comfort zones for air movement with occupant control (darkly shaded) versus without occupant control (lightly shaded).

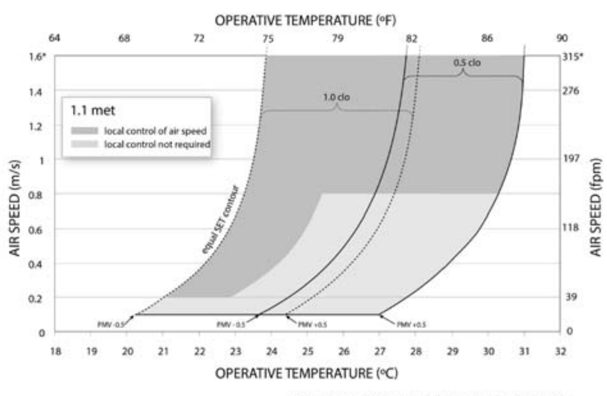

Figure 1: Acceptable ranges of operative temperature to and average air speed Va for 1.0 and 0.5 clo comfort zones at humidity ratio 0.010, according to the ASHRAE Elevated Air Speed Comfort Zone Method [29]

Where there are fans (that can be controlled directly by occupants) or other means for personal air speed adjustment (e.g. personal ventilation systems, or personally operable windows) it is permitted to consider an increase of the upper acceptability temperature limits by the corresponding $\Delta t0$ reported in Table 1:

Table 1: Increases in acceptable operative temperature limits (Δt0)
in occupant-controlled naturally conditioned spaces according to [58]

Average Air Speed V_a [m/s]	Δt_0 [°C]
0.6	1.2
0.9	1.8
1.2	2.2

3 BIOCLIMATIC ARCHITECTURE AND PASSIVE SYSTEMS

The EU's buildings remain generally inefficient, accounting for 40% of final energy consumption and 36% of the EU's total CO_2 emissions [57]. The HVAC systems are one of the main contributors for the increase in energy consumption, being expected that in non-residential buildings, the energy use due to cooling will increase by 275% by 2050 [45].

The use of bioclimatic principles (geometry, orientation, shading...) and passive cooling systems should be strongly encouraged. As for the use of Natural Ventilation to this purpose, using the nomenclature of Givoni [22] we can distinguish (among the passive cooling systems):

Comfort Ventilation: When the indoor temperature, under still air conditions, seems to be too warm to occupants, it is possible to provide comfort through higher indoor air velocity. This strategy is useful when indoor comfort can be experienced at outdoor air temperature (up to about 30°C) with acceptable indoor air speed. If conditions are not favorable for opening windows, increase air velocity with well-designed and positioned ceiling fans, standing fans, and desk fans.

Nocturnal Ventilative Cooling: Night ventilation cools building masses by convective exchange with outdoor air. During the daytime, cooled masses can serve as a heat sink for solar and internal heat gains and ventilation should be minimized. Daytime comfort ventilation and nocturnal ventilative cooling are in many cases mutually exclusive. Figure 2, taken from [29] gives a qualitative idea of the type of climates where the two systems may be usefully adopted.

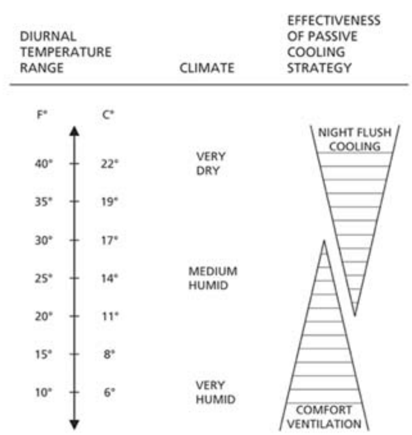

Figure 2: The performance of night-flush cooling and comfort ventilation is a function of diurnal temperature range (max – min outdoor temperature). Note that Lechner uses the term "night flush cooling" for the passive system which Givoni calls "Nocturnal ventilative cooling" [43]

Architectural design based on bioclimatic features has long been of interest to many designers. The literature review conducted by ABC21 [12] offers a non-exhaustive but rather complete view over the type of guidance available, particularly for the pre-design stage, where the most important and impactful decisions need to be taken, many details are still missing, and hence it is more important to apply well proven and understood physical knowledge, rather than performing complex numerical simulations.

The ABC21 Final Report highlights that several guidelines and studies have been developed in the last decades [10] targeting different areas and strategies. Most of these guidelines, also due to their date of publication, do not present in detail an up-to-date description of the comfort models and the comfort objectives to be used as a target for the design and for the assessment of the results achieved. The guidance that can be found is of the type offered in the examples below.

3.1 Guidelines

Site: Choose site with east-west building orientation. Main openings should face north or south (depending on hemisphere)

Form: Prioritize east-west elongated, compact layouts. Use atriums to centralize lighting and views. Use covered atriums for greater compactness. Adapt facade design based on solar orientation.

Plan: Use open designs in hot and humid climates. Compact layouts are favored in hot and arid regions for shading and cool spaces. Integrate plant and water features for cooling. Use buffer spaces on east and west sides. Discourage short elevator trips to promote physical activity. Implement open floor plans to maximize daylight and ventilation.

Windows: Design openings for ventilation and daylight based on climate. Larger openings for hot, humid climates. Smaller openings for hot, arid and semi-arid regions. Limit windows on east and west facades. Emphasize north or south orientations for more openings. Position windows to maximize daylight. Consider operable windows with cooling shut-off when open. Install low-transmittance windows or provide indoor night insulation in cold climates.

Daylighting: Utilize light shelves on east, west and south windows. Opt for high ceilings. Consider clerestories for top lighting. Avoid skylights. Use atriums with north or south-facing clerestories (depending on hemisphere). Explore light tubes, high R-value light-transmitting roof panels and prismatic daylighting glass. Use indoor blinds for glare control. Limit translucent walls. Maximize borrowed light with glass partitions and doors. Use light-colored paving outside first-floor windows for daylight enhancement.

Shading: Implement solar radiation protection for all openings. For east and west windows, use outdoor blinds, roller shades, horizontal louvers, avoid vertical fins. Use trees and plants for natural shading. Test shading designs to prevent solar outflanking. Extend shading to roofs, walls, and landscape. Prioritize vegetated walls on east and west sides in taller buildings. Prefer outdoor shading over indoor. Choose glazing to suit heating requirements and ensure shaded windows during overheated periods.

Color: Use light or reflective external surfaces to minimize sun energy collection and re-irradiation. Prioritize greenery and reduce paved areas. Enhance lighting efficiency with high-reflectance white ceilings, light-colored walls, furniture, and floor finishes. Aim for well-lit spaces with minimal lighting demands.

Thermal mass: Favor light-weight building envelopes in hot and humid climates. Opt for medium-weight structures in hot semi-arid/savannah regions. Ensure mass is exposed to airflow for nocturnal ventilative cooling, avoid covering it with insulating materials. Use sound absorption acoustic panels and partitions.

Glazing: Use various types on each facade and within windows for optimal daylighting. Use insulated translucent panels instead of glazing for clerestories and small skylights, avoid them on lower walls due to glare. Do not use reflective glazing if it causes glare or overheating, nor single glazing for heated or cooled buildings. Use outdoor shading devices to block direct solar radiation and glazing with low solar heat-gain to block diffuse and reflected radiation.

Air barrier: Where heating is required implement air barrier to reduce infiltration. Use high-quality weatherstripping on windows and doors to reduce infiltration. Consider a vestibule or revolving door at the entrance. Opt for a heat exchanger ventilation system for indoor air quality.

Natural ventilation: Employ solar and stack-effect chimneys. Install cowl-type roof ventilators. Use exterior wing walls to divert wind and maximize airflow.

3.2 Advanced Natural Ventilation

Other approaches, like the design method described by certain authors as Advanced Natural Ventilation aim at creating zones protected from noise and pollution from where to draw the intake air [34]. One of the geometrical arrangements of the spaces relies on a one or more central lightwells or courtyards and stack chimneys at the outer border of the building to create a center in edge-out air flow (Figure 3). Intake air is drawn from these central protected spaces. The resulting air flow is "essentially wind neutral, that is, wind pressures will not hinder, or assist, the airflow; this gives added reliability to predictions of their likely, as-built, performance." [34]

For certain nonresidential buildings, unoccupied at night, the night (only) ventilation strategy might allow to flush out energy at night when the absence of occupants removes the problem of disturbance by external noise. In some European cities the extension of pedestrian areas and the reduction of speed to 30 or 20 km/h as e.g. in Paris, might offer new spaces where the problems associated with noise and pollution are removed or significantly reduced. For new areas to be developed for the growing African population, a clear view of the need to co-design building and districts might help to create positive conditions for natural ventilation.

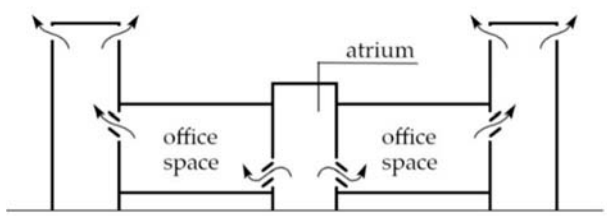

Figure 3: Schematic diagram of stack ventilation "center-in, edge-out", drawing air from a space relatively protected from noise and pollution. Source: [43]

3.3 Bio-climatic charts

When designing bioclimatic buildings, it is common to use bioclimatic charts, which are simple tools that consider climate conditions to recommend appropriate design for different climates. Various types of bioclimatic charts have been developed such as the Olgyay Bioclimatic chart, the Givoni–Milne Bioclimatic chart, the Szokolay Bioclimatic chart and the Mahoney Table [49]. For hot climates, it is recommended to use the Givoni bioclimatic chart. The originality of the work proposed by Givoni is to use the psychrometric chart as the base layer to characterize comfort zones [21,22].

Givoni has developed several comfort zones depending on:

- the level of air velocities on the users (0 to 2 m/s);
- the level of development of countries (developed countries and developing countries).

For developing countries, the upper limits of accepted temperature and humidity are higher than in developed countries, assuming that people are acclimatized to hot and humid conditions.

The Givoni bioclimatic chart is a useful tool to assess thermal comfort at the design stage or during the post occupancy evaluation process (Figure 4).

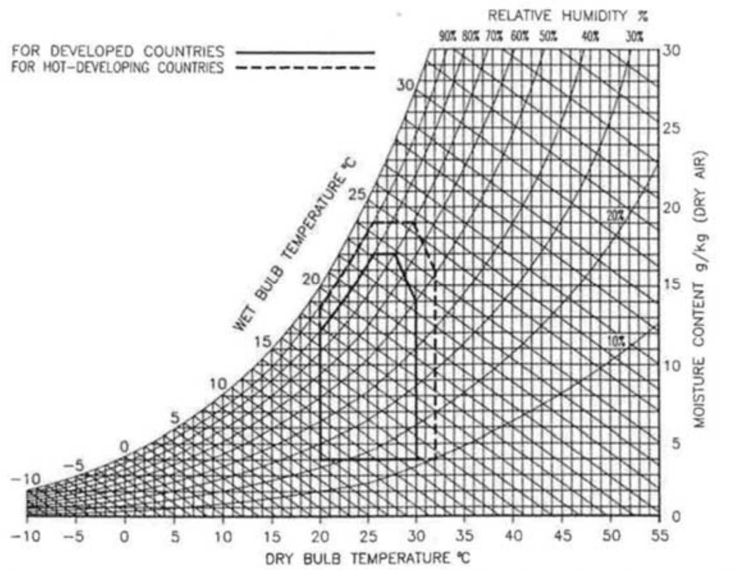

Figure 4: Comfort zones defined by Givoni [21,22] for an air speed of 2 m/s

3.4 The KPIs to support bioclimatic design

Key Performance Indicators (KPIs) are essential to quantify the building performance, detect malfunctioning or misuse of the building by the occupant or users, synthesize complex information. Several KPIs for thermal comfort assessment are available in literature and standards. Two main categories can be identified:

- indices that focus on comfort conditions at a certain time and position in space (e.g., the ASHRAE Likelihood of Dissatisfaction ALD [6], the overheating risk index NaOR [38])
- long-term comfort indices that aim at assessing thermal comfort quality of a building over a span of time and considering all the building zones [7].

Table 2 reports a selection of the reviewed indicators for assessing thermal comfort in bioclimatic buildings. They can be used to monitor and verify the conditions of the indoor thermal comfort in buildings, offer a comparison between the case studies and provide guidelines for bioclimatic design in warm climates.

Table 2: Long-term thermal comfort indicators

n	Thermal comfort index	UoM	Definition
1	Percentage of time outside an operative temperature range (Adaptive)	%	Calculate the number or percentage of hours, during the hours the building is occupied, the operative temperature is outside a specified range calculated according to the adaptive thermal comfort model.
2	Percentage of time outside an operative temperature range (Fanger)	%	Calculate the number or percentage of hours, during the hours the building is occupied, the operative temperature is outside a specified range defined according to the Fanger comfort model.

3	Degree-hours (Adaptive)	h	The time during which the actual operative temperature exceeds the specified range (calculated according to the adaptive thermal comfort model) during the occupied hours is multiplied with a weighting factor which is a function of how many degrees the range has been exceeded. The product of each hour for the corresponding weighting factor is then summed up over the period of interest, (e.g. summer)
4	Degree-hours (Fanger)	h	The time during which the actual operative temperature exceeds the specified range (defined according to the Fanger comfort model) during the occupied hours is multiplied with a weighting factor which is a function of how many degrees the range has been exceeded. The product of each hour for the corresponding weighting factor is then summed up over the period of interest, (e.g. summer)
5	Percentage of time inside the Givoni comfort zone for air velocity at 1 m/s	%	Calculate the number or percentage of hours during the hours the building is occupied, when the pair "operative temperature/relative humidity" is inside the specified comfort zone
6	Percentage of time inside the Givoni comfort zone for still air conditions, i.e. v = 0 m/s	%	Calculate the number or percentage of hours during the hours the building is occupied, when the pair "operative temperature/relative humidity" is inside the specified comfort zone
7	Number of hours during which the operative temperature is within a certain range	-	Calculate the number of hours during which the operative temperature is within a certain temperature range

4 PROPOSED DESIGN METHODOLOGY

The design process must be carried out logically and sequentially since passive design requires to consider the features of the entire building, not just elements or machines in isolation. This is intended to minimize solar and heat gains and maximize the ability of a natural ventilation system to remove the cooling load. A Natural Ventilation design procedure consists of different phases, namely: conceptual design phase, basic design phase, detailed design phase and design evaluation. The Figure 2 illustrates the design procedure of a ventilation cooling system.

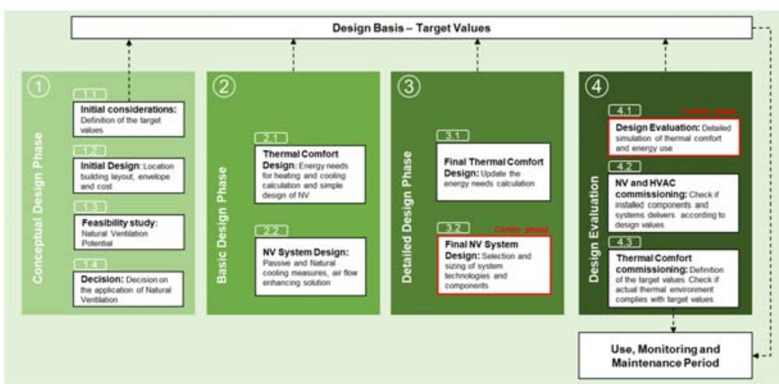

Figure 2: Design procedure for Ventilative Cooling

4.1 Conceptual Design Phase

In the first step of this phase, the desired level of thermal comfort and energy performance objectives are defined, along with other requirements. Target values are set for metrics to assess thermal comfort and energy performance. Energy use targets and costs (preferred life cycle cost) are also defined. The potential for Ventilative Cooling (VC) of the local climate is analyzed, considering factors like weather, opening type, building use, internal gains, and envelope characteristics.

Urban environments present challenges for natural ventilation due to wind disturbances, elevated air temperatures which decreases the stack effect [20], air pollution, and noise [8]. The ABC 21 case studies demonstrate strategies to reduce noise, pollution, and temperature using trees and limiting cars. Newer, quieter mobility solutions like e-bikes, electric public transport, and shared mobility are expected to improve urban environments.

Simplified models are used initially to assess VC potential based on internal loads, building characteristics, surrounding environment, and local climate. Supplementary natural or mechanical cooling systems may be needed to meet thermal comfort requirements during the hottest months.

A broad range of solutions are considered during the conceptual design phase. If a Natural Ventilation strategy is chosen, the potential benefits of a hybrid ventilation configuration (NV assisted in certain moments by fans) are analyzed. Table 3 and Table 4 provide a procedure for assessing if a hybrid strategy or additional cooling systems are needed. This procedure is iterative, and options involving "Yes" should be avoided to prevent additional costs and delays. Increased "Yes's" involve increased risks, to be evaluated in building contracts. Expert consultation and references to well-documented case studies are recommended.

Tables outline design concepts and boundary conditions for NV use, divided into categories (F1-F5 and C1-C4). Users select the relevant options for their case study, choosing only one option if multiple are available. Blank spaces in the tables represent available choices. First, users determine the need for additional mechanical/fan assistance or cooling systems based on building program data. The responses can be 'No', 'Maybe', or 'Yes'. Next, users define VC concepts for analysis or consider building modifications that reduce mechanical assistance need. The procedure in Table 3 and Table 4 is iterative. Avoid 'Yes' design concepts to implement certain ventilative cooling concepts without added costs and delays. Increased 'Yes' responses may raise risks, warranting consideration in construction contract discussions. Consulting expert guides and case studies on buildings with similar exterior conditions is advised.

Table 3: Survey of the need for supplementary natural or mechanical cooling solutions for CML kindergarten, Portugal.

Ventilative cooling system: is there a need for supplementary cooling?						
C1. Outdoor environment		**N**		**M**		**Y**
C1.1.2. Temperature (2-10°C from comfort zone)				O		
C1.2. Dense urban area with low wind speeds (low natural driving force)				O		
C1.3. Dense urban area with high night temperatures (heat island)			**O**			
C1.5. Noisy surroundings				**O**		
C2. Building heat load level		**N**		**M**		**Y**
C2.1.3. High internal loads > 30 W/m2 during occupation	Temperate (2-10ºC from comfort zone)			**O**		
C3. Thermal comfort		**N**		**M**		**Y**
C3.1.4. Normal requirements for 90% of occupancy hours				**O**		
C4. Building and system		**N**		**M**		**Y**
C4.1.3. High level of exposed building thermal mass		**O**				
C4.2. High space- and use-flexibility			**O**			

Table 4: Survey of the need for mechanical assistance (by fans or additional passive means) for CML kindergarten, Portugal.

Ventilative cooling: Is there a need for mechanical assistance (by fans or additional passive means)?						
F1. Outdoor environment		**N**		**M**		**Y**
F1.1.3. Hot and dry	Winter	**O**				
	Summer (low temp. difference)			**O**[1]		
F1.2. Dense urban area with low wind speeds (low natural driving force)					**O**	
F1.5. Noisy surroundings (high noise insulation needed)				**O**[2]		
F2. Building heat load level		**N**		**M**		**Y**
F2.1.3. High heat loads > 30 W/m^2 during occupation	Cold (> 10ºC from comfort zone) (heat recovery needed)	**O**[3]				
	Temperate (2-10ºC from comfort zone)	**O**[3]				
	Hot and dry (-2ºC …. +2ºC from comfort zone)				**O**[1]	
F3. Thermal comfort		**N**		**M**		**Y**
F3.1.4. Normal requirements for 90% of occupancy hours					**O**[3]	
F5. Building and system		**N**		**M**		**Y**
F5.1.3. High level of exposed building thermal mass		**O**[4]				

4.2 Basic Design Phase

During the conceptual design phase, VC availability is analyzed, and solutions are defined to achieve objectives. The basic design phase unfolds in three steps, beginning with orientation and layout designed to minimize internal heat loads and to create airflow paths to effectively remove the excess of heat loads. Poor decisions here significantly impact passive cooling and overall performance. Factors like window-to-wall ratio [15], shading devices, and thermal mass are vital [36]. Orientation also greatly influences NV system performance [19]. In climates and during season with a significant day-night temperature swing, high thermal mass buildings can utilize Nocturnal Ventilative Cooling to reduce operating temperature by 2 to 4 degrees [8]. Solar gains are the main factor that should be controlled in summer for optimal occupants' comfort and energy consumption.

The second step involves developing the NV system with supplementary strategies to increase the Ventilative Cooling capacity if necessary. Natural Cross Ventilation (NCV) and Single-Sided Ventilation (SSV) the most common approaches in naturally ventilated buildings. NCV's effectiveness depends on wind speed and direction, which can create discomfort due to intense drafts. The stack effect and wind effect increase the NV potential in SSV configurations. The same is not true for NCV configurations since the configuration of the openings can oppose the natural driving forces [8]. Thus, in NV systems with NCV configurations, the zones should have a geometry that allows an optimized exhaustion. The inlet airflow is made by a lower zone in the facade and extracted at the top of the opposite facade [8], and therefore avoiding the opposing forces. Still, the airflow in SSV is usually smaller than in NCV systems, so they have less cooling potential [4]. Buildings with narrow footprint or large spaces with high ceilings are design techniques that favor the performance of a NV system [8]. According to experimental data in areas with high-ceiling buildings, the stack effect is quite efficient [15]. In SSV configurations the penetration depth of NV is usually equal to twice the zone's height; therefore, these configurations perform best in areas with low depth and high ceiling heights [8]. CIBSE recommends that the maximum zone depth for single-sided systems should be 2.5x the zone height. However, experimental studies have shown that these limits are very restrictive, and depths of 3H can be achieved [53]. On the other hand, for NCV, the depth of the space should not exceed five times the height of the space [54]. In buildings where there are areas with constant occupation and low height, it is necessary to implement chimneys or N systems to promote a fresh air intake [8].

High-rise buildings are less influenced by their surroundings than low buildings, which makes the wind an additional driving force to achieve the desired airflow rates [50]. Due to the decreasing of temperature with height, the upper half of these buildings can take advantage of the lower temperatures to exploit NV systems [8]. Tall buildings are subject to large pressure differences [41] since wind speed and pressure also increase with height [25]. Increasing wind speed results in increasing airflow, and a linear relationship has been found between wind speed and airflow for all wind directions independent of the number of openings [26]. Thus, in tall buildings, the NV system must operate differently in the first 4-6 floors due to the lack of wind-driven NV arising from the barrier effect caused by the surrounding buildings [8]. In high-rise buildings, this increase in pressure with height leads to some problems in the design of the opening area and type. In wind-driven ventilation, the airflow follows the pressure gradient and can be realized by other systems, such as wind catchers [54]. Wind catchers have demonstrated high performance in hot and dry climates [3,28].

The third step is the combination of different passive systems. The use of a single ventilation strategy may be insufficient. It has already been shown that combining earth-air heat exchangers (EAHE) with solar chimneys is a very effective strategy for maintaining thermal comfort in severe weather conditions [35]. According to [32], these systems achieve a temperature reduction of 10º to 13º with respect to the outdoor temperature. In the EAHE technique, the underground is used as a heat sink to supply air to the building at a constant temperature [35]. Another widely used strategy to improve the performance of natural ventilation systems is coupling passive storage systems such as Phase Change Materials (PCMs). According to the literature, coupling these passive storage systems with solar chimneys can increase the number of ventilation hours [33]. The coupling them with wind towers has also been shown to be quite effective, reducing the air temperature between 9ºC and 12ºC [5]. In areas where the wind is not predominant and, therefore, wind-driven ventilation is not efficient, the combination of solar chimneys with wind catchers can be a solution that increases the efficiency of the natural ventilation system. In this last step of the basic design phase, mechanical cooling systems are designed to supplement passive cooling systems in periods when they do not have the necessary capacity.

4.3 Detailed Design Phase

The final design phase involves optimizing the developed solution. Key components like the ventilation system's openings are determined, including their type, size, and location. An effective simulation model is crucial to optimize the design, but it needs accurate input data and skilled handling to provide reliable results. Several issues must be considered, such as the correct specification of the relevant boundary conditions, evaluation and justification of the model simplifications, decision on the necessary time discretization, and evaluation of the risk associated with using detailed performance simulation model.

For passive cooling system design, understanding the parameters that affect performance is essential. Factors that affect solar and internal gains have a dominant influence on reducing the cooling demand. In contrast, the discharge coefficient and the opening factor notably impact the number of hours of comfort. The required airflow rate is critical in determining the ventilation strategy, and the size and location of the openings must be optimized for different scenarios.

For Comfort Ventilation, ceiling or desk fans may be necessary when wind or stack driving forces are insufficient to achieve the desired air velocity. Modern fans come with aerodynamic design and efficient motors that can be remotely adjusted for speed. They also offer high stability against oscillations, low noise levels, and very high energy efficiency. The number of blades can vary, and a fan's efficiency increases with larger diameters. Tools like CFD analysis or simplified tools can assist in fan size selection and distribution.

4.4 Design Evaluation

Finally, detailed simulations of thermal comfort and energy use are made in the design evaluation phase to control whether the design meets the project objectives. The design tools and methods' wealth of detail and complexity increase as the design develops. The level of detail of the information and expectations about the accuracy of the predictions' results also increase.

5 CONCLUSIONS

The paper based on *ABC21 Final Report on UPDATED technical guidelines and tools* offers an updated view of the future of bioclimatic architecture (which might be the architecture in a climate-compatible future of humanity) and passive systems under the new boundary conditions of XXI century, while taking advantage of accumulated wisdom and the work of the pioneers of XX century.

Bioclimatic architecture and passive systems are a key element of the future, with their evolution for considering the changes in climate, take profit of the improvements in local geo- and bio- based materials and the availability of totally new materials as the ones able to passively radiate more energy to the deep sky than they absorb from the sun. We aim at promoting to university and vocational training the use of the present guidelines and other training tools (reports, simplified pre-design tools, analysis of case studies, recording of webinars etc.) developed within the project. Those training activities should also be an occasion of breaking the harmful barriers between architects and engineers, with difficulties in quantitative analysis on one side and biases towards complex technologies and calculations, sometimes disconnected from user's needs and practical design, on the other side.

More work is needed, but we hope this collaboration between Africa and Europe offers suggestions for taking steps in the right direction.

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