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Skin Facade Design for the Thermal Balance in the Mantaro Valley Buildings

Oriana Ximena Arias Coz
Marycielo Cyntia Olivera Buendia
Vladimir Simón Montoya Torres

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Autores:
1. Oriana Ximena Arias Coz – EAP. Arquitectura
2. Marycielo Cyntia Olivera Buendia – EAP. Arquitectura
3. Vladimir Simón Montoya Torres – EAP. Arquitectura

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Skin Facade Design for the Thermal Balance in the Mantaro Valley Buildings

Marycielo Cynthia Olivera Buendia[1,*], Oriana Ximena Arias Coz[1], Vladimir Simon Montoya Torres[2]

[1]Faculty of Engineering, Professional Academic School of Architecture, Universidad Continental, Peru
[2]Faculty of Engineering, Universidad Continental, Peru

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Abstract Climate change significantly impacts the lifestyle of people living in high Andean areas. For children, heat, combined with other environmental factors like humidity, leads to exhaustion—something experienced daily. Prolonged exposure to heat can cause side effects such as anxiety, and depression, and contribute to mass migrations and regional conflicts, affecting local communities. Given these concerns, this research focuses on the thermal comfort of all types of buildings, whether residential or public. It proposes the importance of controlling internal temperatures, much like green walls or building placement systems that allow air to flow freely, creating cool chambers with stable temperatures for a greater sense of comfort. To achieve this, a system of modular architectural membranes was designed and prototyped. These membranes are tailored to the specific needs of the geographical region where the study was conducted, as each area requires dynamic, flexible geometries capable of forming responsive and intelligent morphologies. The results have effectively met the thermal control needs of buildings in the Mantaro Valley, complying with ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) standards for thermal comfort. Additionally, the system integrates high Andean cultural elements, preserving traditions and art to reinforce identity, as expressed through iconography in the "lliclla," a traditional Andean mantle. Finally, it's important to mention that various tools were used throughout the data collection, implementation, and design modification processes. SketchUp and V-Ray were utilized for design and presentation; MS Excel, Meteonorm, and WeatherSpark for pre-prototype data collection; and GeoGebra and Climate Consultant for adjustments and changes due to external factors like sudden temperature shifts and the structure of the building where the prototype data was collected.

Keywords Climate Change, Heat Capture, Thermal Control, Domopathies, High Andean Identity, Modular Architectural Membrane, Architectural Skin, Thermal Regulation, Sustainability

1. Introduction

Climate change is a problem that has been worsening since the last century since climatic zones are changing, glaciers are in a constant process of melting, and sea levels are rising [1]. These are effects that were mentioned many years ago, in addition within the contemplations it was noted that the temperature was going to increase more and more, in the same way, there would be massive decreases in other locations, all of which are due to the effect generated by environmental pollution and the greenhouse effect caused by the increase in temperatures. It also produces effects such as "direct cooling" because it affects not only living conditions, but also agricultural production, and in other cases, livestock activities.

Among the direct consequences that can occur due to the increase in temperature, there are mainly cases in children, which, due to the strong sensation of heat and environmental humidity, causes them to be in a state of fatigue generated by the global temperature increase. In addition, there are other effects such as the higher incidence of worry, depression, the negative impact on mass migrations and regional conflicts [2], which are considered a strong blow to minimum living conditions because climate change is affecting both the mind and the place in which one lives, causing people to seek a more optimal environment to develop. About the harmful effects on children's health, according to the United Nations Children's Fund (UNICEF), it was found that a total of 377 children in countries between Europe and Central Asia lost their lives due to the effects of extreme heat, 48% of whom were children who were not even in their first year of life. Also in the year 2024 it shows that according to the Disability Adjusted Life Years (DALYs) indicator a total of 32,356 healthy life years were lost [3], furthermore in the fact sheet provided by the non-profit news organization "Climate Central" entitled: "Climate Change and Children's Health: Extreme Heat" shows that in the United States of America about 9000 adolescent athletes are seen annually for cases and conditions related to high temperatures, also that 12% of children's hospital admissions are directly related to illnesses or conditions caused by heat between the months of May and September, which is summarized in 17000 annual visits to the doctor [4].

So, considering the above, it is known that it is elemental to focus on thermal comfort inside buildings so these extreme temperatures can be counteracted and generate a barrier system that helps control stress levels and related backgrounds; similar to the problem raised by the research, which proposes the implementation of green walls to control the internal temperature [5]. It is considered especially important to generate a system that can be coupled to vertical surfaces, generating the desired thermal control, in addition, related to this, it can be reviewed that there were precedents worldwide about bio-walls, which, more specifically, were considered biostructures for the conservation of internal temperature. Consequently, many of the buildings that are now called traditional buildings were built due to architectural evolutions related to the comfort of the inhabitants, construction strategies, immediate needs, and fundamental cultural influence [6]. A clear example of these is primitive homes, which can be highlighted because they prioritized the capacity to retain heat internally in the case of those located in areas with rapid temperature drops; in other cases, some considered caves as a place to take refuge from the hardness of the environment; and finally, those who were sheltered in ecosystems in which wetlands or swamps were the ones that prevailed [7].

With human evolution, other needs arose in the search for thermal comfort, and civilizations were born that took advantage of their immediate closest resources to generate optimal thermal comfort for their cities. An example worldwide and about ancient cultures is Machu Picchu, which would be original Solar City of America, because it condensed so many construction techniques with the use of materials that generated comfort within its buildings; one of them would be the city that is oriented towards the east, because it takes advantage of sunlight during the first hours of the day efficiently by being in a location surrounded by high peaks. These worked by controlling the formation of clouds during the summer to regulate the sensation of heat and during the night they provided a distribution of high temperatures as a result of the accumulation of heat during the day. Finally, during winter, it worked so that during the day heat was stored, taking advantage of the low formation of clouds, and when night came, it could retain the internal heat gains in the city walls [8].

Due to the industrial revolutions, there has been an overuse of glass and mechanical devices for temperature control, which has contributed to global warming and the energy crisis. The most prominent consequence of this is the lack of commitment to the environment. This situation is also observed in Bolivia, where the government does not encourage research in the energy and environmental fields, which generates a great need among the inhabitants. This lack drives the search for immediate solutions. In this context, the research entitled "Bioclimatic social housing for Santa Cruz de la Sierra, Bolivia" mentions that bioclimatic housing focuses mainly on energy savings, but lacks an effective internal temperature control system. In the development of this research in Bolivia, data were presented such as that one of the most effective ways to moderate the temperature is by adding eaves on the windows or small elements that prevent the entry of solar radiation, either partial or total. In addition, the orientation of the house, the design of its windows and its structure in general have a great impact on temperature regulation. It is crucial to consider the use of materials with a high thermal transfer retarding capacity or with high thermal inertia on external surfaces [9].

Thus, in the near context, the mountain ranges of the Andes, as well as those of the Himalayas, are areas that have the highest altitude cities in the world; in the Andes is La Rinconada, a city at 5000 m a.s.l. with 1000 inhabitants, being the highest city in the world, while the Andes has 109 cities between 3000 and 4000 m a.s.l. Grouped as Meso-Andean zones, these are why strategies must be generated to maintain due thermal comfort both internally and externally [10]. Within the basic concepts for the construction of buildings, it is recommended to follow the technical standard of the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) of 2005 [11], in addition to being convenient to take advantage of the property of thermal inertia, because it can increase the internal temperature of an environment by up to 11.9% according to studies carried out in Cusco [12].

In Peru, the National Standard for Electrical and Mechanical Installations (EM 110 Thermal and Light

Comfort with Energy Efficiency) separates the different departments according to their bioclimatic factors, and in the same way, divides each area of each department by the following denominations: marine desert, desert, low inter-Andean, meso Andean (Table 1), high Andean, snow-capped mountain, mountain eyebrow, humid subtropical and humid tropical [13]. Since the project is located in the Meso-Andean, its zone's special characteristics are highlighted.

Table 1. Bioclimatic characteristics of Junín by bioclimatic zones from National Standard EM 110 Thermal and Light Comfort with Energy Efficiency

CHARACTERISTICS	MESO-ANDEAN ZONE
Average annual temperature	12 ℃
Average Relative Humidity	30 to 50 %
Prevailing wind direction	S - SW
Wind Speed	North 10 m/s, center 7.5 m/s, south 4 m/s, south-east 7 m/s
Solar radiation	2 to 7.5 kWh/m^2
Hours of sunshine	North 6 hours, center 8 to 10 hours, south 7 to 8 hours
Annual Precipitation	150 to 2500 mm
Altitude	3000 to 4000 m a.s.l.
Equivalent in Koppen classification	Dwb

In addition, the International Organization for Standardization (ISO) 7730 standard, mentions that thermal comfort is expressed according to the state of comfort that a person has to ambient humidity, temperature, air speed, and radiation, in addition to the number of individuals that are within the same environment [14]; taking into account the considerations previously mentioned, this article focuses on supplying a control within some of the factors that lead to thermal comfort, heat, humidity and air speed as the main thermal actors, which will be modified through the design and subsequent implementation of architectural skins suitable for the Mantaro Valley and specifically in the city of Huancayo.

To fulfill this intention, it is convenient to design architectural skins, which will be used with the mobile systems generated by the applications and modulations of this type of structure that has a linear, superficial, and spatial grouping [15], to obtain almost infinite variations in the ability to locate it in any building. This allows older buildings that need to generate comfort to benefit from this design, thus benefiting not only with functionality but also with the ability to renew their appearance and aesthetics; in addition, to have additional functionality for the city of Huancayo, which would be the ability to redirect the water generated by rainfall slightly.

The consideration benefits that are obtained in a general way when using these structures are the ease of assembly and construction [16] because the entire system is modular way, to carry out its assembly is similar to the modular toys of the Lego brand, thus having two of the main characteristics that are intended to be fulfilled; firstly, the ability to generate complex facades with only the use of simple parts, i.e. modules; and, secondly, the ability to retain heat without the need for heavy surfaces, avoiding the potential danger of falls, based mainly on the application of biostructures such as green walls and their methodology, which has a lot to do with materials, orientation and location.

2. Materials and Methods

First, the evaluation and study of the "model of the module" that will be used in the architectural skin are carried out based on the environmental conditions of the city of Huancayo. For this, the basis is the studies carried out by Xiao Zhang in 2021 and Hernández in 1984, who, in their studies, have been able to determine the feasibility of each modular form. Depending on the use, they presented a list of possible forms that can be given to them, including the Waterbomb Pattern and Diamond Pattern [17], the most optimal for flat structures; and thus, also, to be able to carry out the second purpose, which is the redirection of rainwater.

To perform the mathematical calculations related to the study, it must be taken into account that comfort within an architectural environment is largely denoted by the materials and each of the characteristics that it brings to the environment since they maintain a balance internally, to have a virtually constant temperature throughout the time [18], but this is variable concerning the context that was studied. In this case, the Mantaro Valley, more specifically the city of Huancayo, has an average annual environmental temperature; according to the website weatherspark.com, which keeps a historical record compiled from January 1, 1980, to December 31, 2016, the average annual temperature of the city of Huancayo ranges between 6 ℃ and 20 ℃ (Figure 1).

On the other hand, the National Meteorological and Hydrological Service (Senamhi) indicates that the average annual temperature in the city of Huancayo ranges from 21 ℃ to 25 ℃ as the maximum temperature and 7 ℃ to 11 ℃ as the minimum temperature, which is a historical average with data taken in a range between 1981 and 2010.

Considering that all the data compilations shown above are from periods between 1980 and 2016, we proceeded to obtain an average current temperature, which has a study period between February 15 and March 10, 2024, which resulted in the average maximum temperature in this period being 17.32 ℃ and a minimum of 8.32 ℃ (Table 2).

Having the data of the average outdoor temperature, the average indoor temperature, or what is considered a standard temperature for thermal comfort must also be evaluated in these aspects, which can be mentioned that making use of standard 55-2.010 of the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) mentions that the optimal temperature range for internal thermal comfort is included in the range of 20 ℃ to 24.5 ℃ (Figure 2).

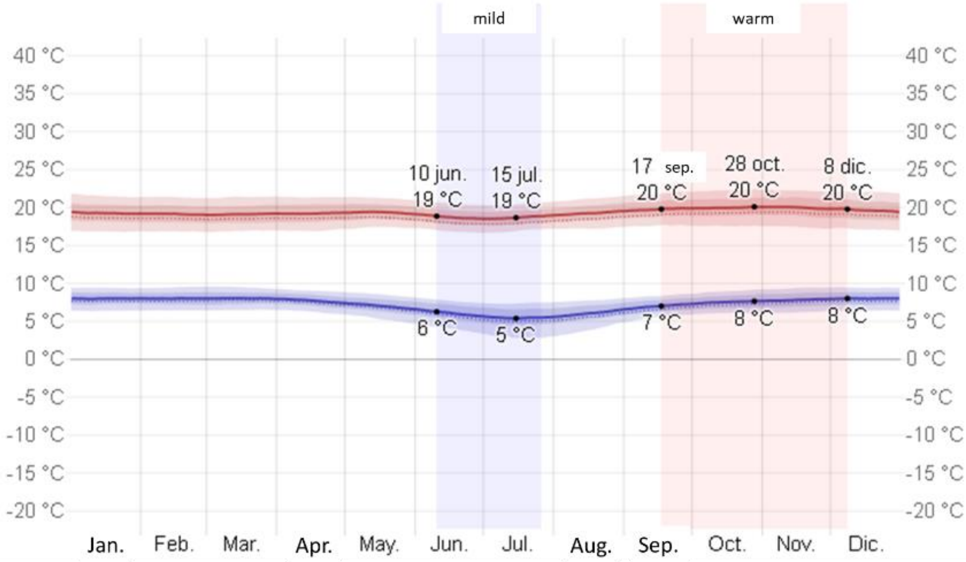


Figure 1. Average temperature in Huancayo January 1980 – December 2016 by © WeatherSpark.com

Table 2. Maximum and minimum temperatures in Huancayo

	Month	Day	Maximum	Minimum
Huancayo Temperature in ℃	February 2024	15	18	9
		16	18	8
		17	19	8
		18	19	9
		19	19	9
		20	19	6
		21	20	6
		22	20	8
		23	18	9
		24	15	8
		25	15	9
		26	16	9
		27	17	9
		28	16	9
		29	17	8
	March 2024	1	15	8
		2	16	8
		3	17	8
		4	17	9
		5	18	9
		6	18	9
		7	15	9
		8	16	8
		9	17	8
		10	18	8
Average			17	8

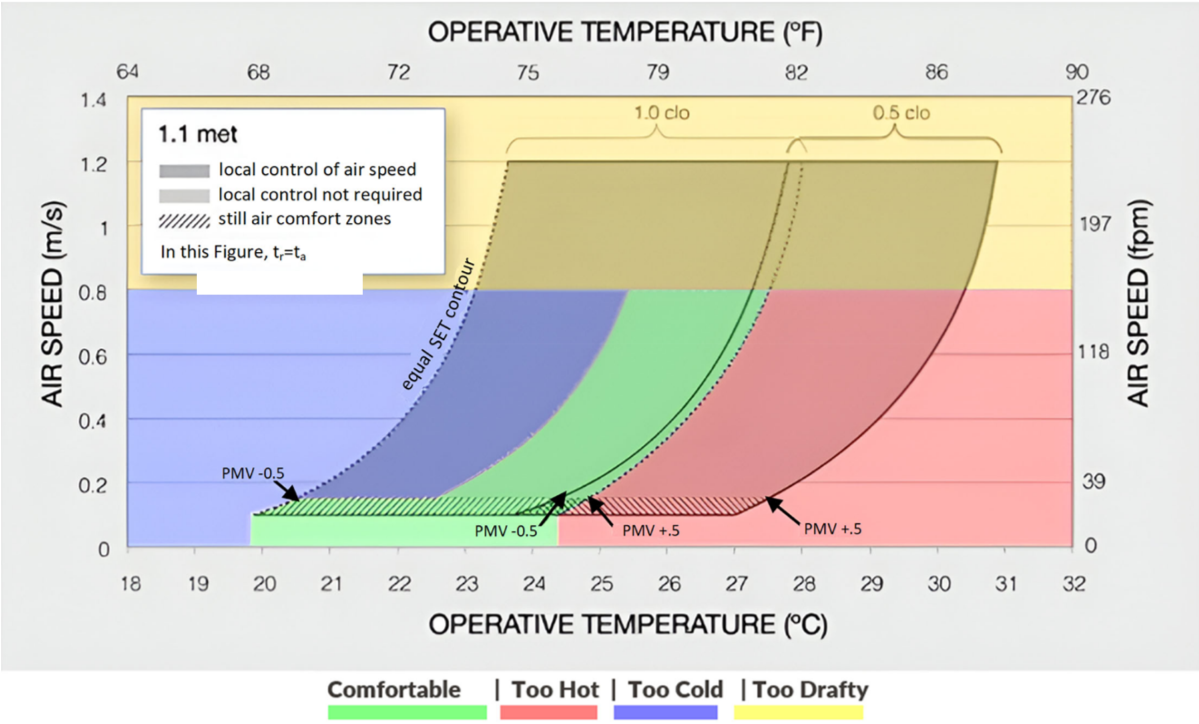


Figure 2. Internal thermal comfort according to ASHRAE 55-2.010

Since already both the external and internal temperatures are obtained with which it will work, the selection of the material is made based on its coefficient or constant of thermal conductivity (λ or k), which is defined as the capacity of energy to be transported in a given time and a solid medium with a cross-sectional area. Also, it has a specific thickness. Among the principal materials that were evaluated for the study, there is the following table specifying these values for subsequent analysis:

Table 3. Thermal conductivity coefficient

Names	Thermal conductivity coefficient (λ) in W/(mK)
Silver	429
Pure aluminium	237
Brass	81-116
Steel	47-58
Stainless steel	12-45

Once we have the materials for the possible selection and also the predetermined needs to generate thermal comfort within the home, we proceed to make the calculations related to the "thermal inertia", which is defined as the heat load capacity of a given built area, about its total mass and its specific heat. The calculations are based on 1 m^2 of a wall of noble material with a thickness of 15 cm and 1 m^2 of glass, with a thickness of 1 cm, this is because they are the most common surfaces that can be observed in the city of Huancayo.

$$Qc = \sum m \ \ .Ce$$

$$Qwwallnoble = mbrick.Cebrick + msand.Cesand + mconcrete.Ceconcrete$$

$$Qwwallnoble = \frac{226.136kgx850J}{kgK} + \frac{70kgx830J}{kgK} + \frac{27.727kgx920J}{kgK}$$

$$Qwwallnoble = \frac{0.1922MJ}{K} + \frac{0.0581MJ}{K} + \frac{0.025508MJ}{K}$$

$$Qwwallnoble = \frac{0.275808MJ}{K}$$

$$QwglassTenvironment = \frac{22kgx780J}{kgK} = \frac{17.16KJ}{K}$$

$$QwglassT > 20°C = \frac{22kgx1100J}{kgK} = \frac{24.2KJ}{K} \quad (1)$$

As part of the calculation, it is also necessary to know the amount of calories generated by the variation in temperature of the selected material, making the calculations based on 1 m^2 of surface with 1 mm thickness, the average maximum and minimum temperature in the city of Huancayo, and the calorimetry formula that is expressed by the following equation:

$$Qbrass = mCe\Delta T$$

$$Qbrass = \frac{8730gx0.09calx(17°C - 8°C)}{g°C}$$

$$Qbrass = 7071.3 \ \ Kcal \quad (2)$$

In this result, you can see the amount of calories or energy that a brass plate with the specifications shown above can directly absorb, but this is under the initial idea that it is subjected to a sudden change in temperature.

Subsequently, the thermal conductivity formula is applied in a time of 6 hours from noon, to a surface equivalent to 1 m^2, a thickness of 1 mm, a maximum temperature of 17 ℃, a minimum temperature of 8 ℃ and the maximum coefficient of thermal conductivity that has the value of 116W/m℃ (the symbol K is replaced by ℃ because as it rises one degree K also goes up one grade C).

$$\Delta Q = \lambda S \frac{\Delta T° x \Delta t}{\varepsilon}$$

$$\Delta Q = \frac{116W}{m°C} x 1m^2 x \frac{(17°C - 8°C)x36000sx6}{0.001m}$$

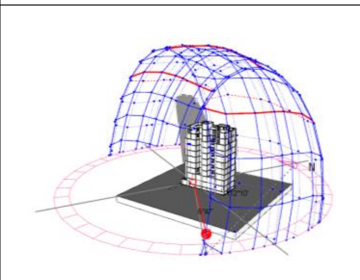
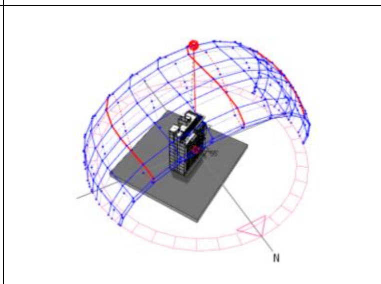
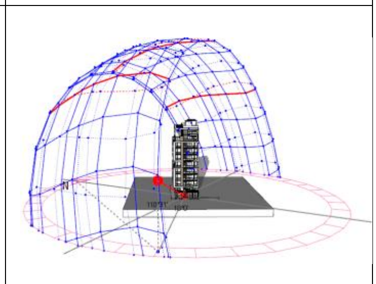
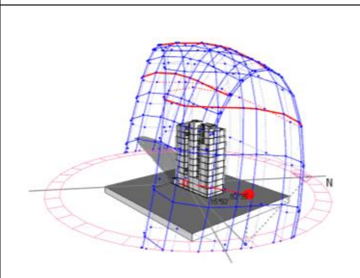
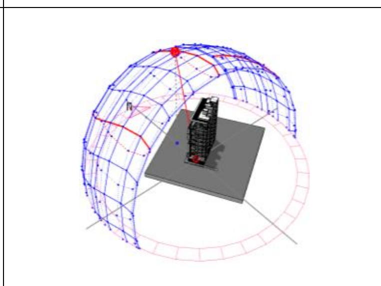
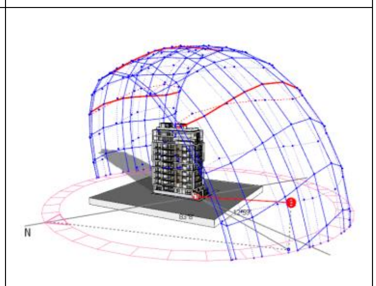
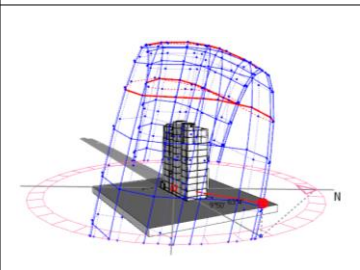
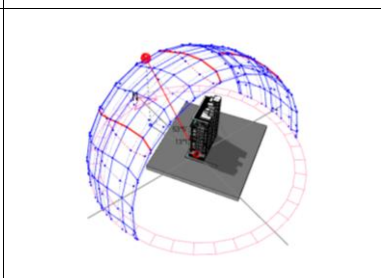
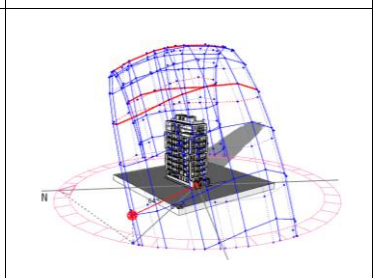
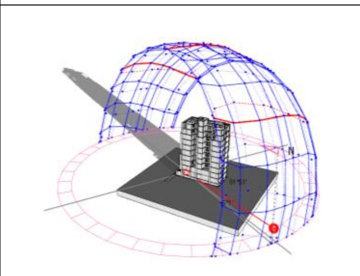
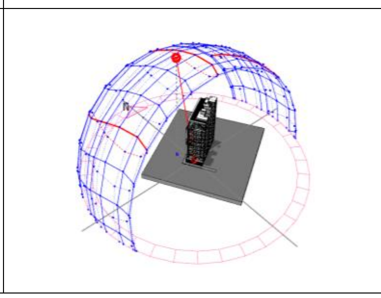
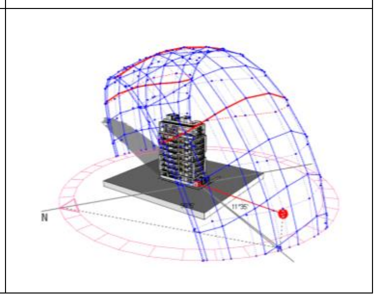
$$\Delta Q = 2.25504x10^{10}J$$

$$\Delta Q = 36000GJ \tag{3}$$

The energy that can be transferred by the brass plate with the specified measurements is a total of 22.5504 GJ over 6 hours.

Next, the analysis was conducted in the SketchUp program, with the CuricSun complement, and the sunlight in a geolocated building in the city of Huancayo was evaluated, taking into consideration the location of the facades in the buildings that respect the rectangular urban grid. It was observed that, during the year, the north facade is the one that receives the most solar lighting; therefore, the east and west facades are at a high level but lower than the north facade, and the south facade, receives little sunlight during the year, as can be seen in the following table:

Table 4. Seasonal solar analysis of buildings in Huancayo using the SketchUp program with the CuricSun add-on

	7:00 a.m.	12:30 p.m.	5:00 p.m.
01 – 01 - 2024			
30 – 03 - 2024			
30 – 06 - 2024			
30 – 09 - 2024			

The above is supported by the solar analysis carried out in the Formit Autodesk programs, because the north, east, and west facades present a medium level of radiation during the year, represented by red; and the south facade, a medium-low level of radiation, represented by a plum color. The entire analysis of the Formit Autodesk program is represented by a color scale, where blue is the area with zero radiation presence, yellow is the yellow area with the highest presence of radiation throughout the year, and red is a transitory value in the aforementioned rating scale (Figure 3-4).

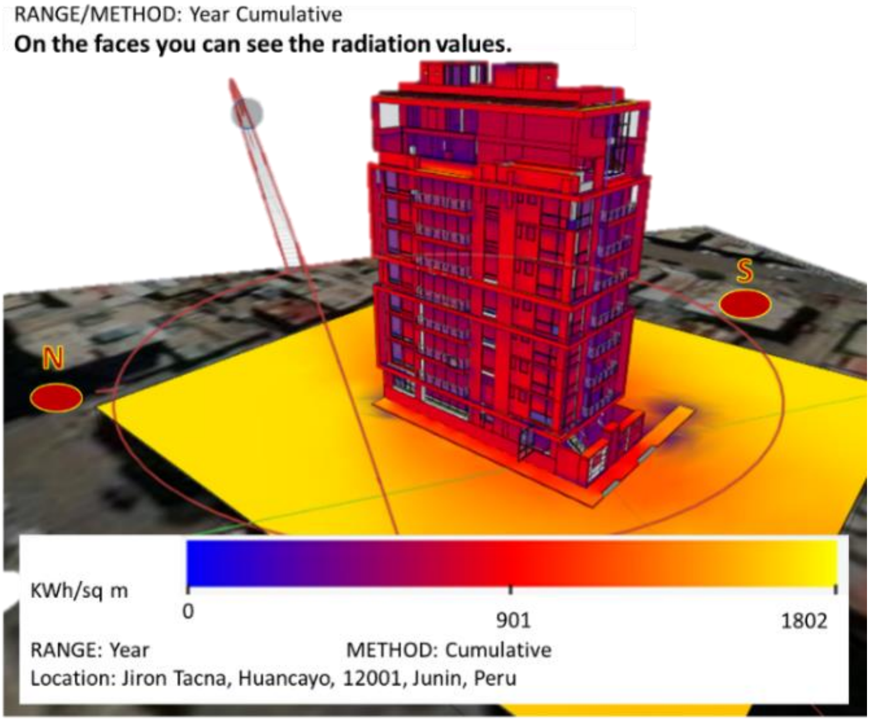


Figure 3. Solar analysis of north facade using the Formit 2024.1. program

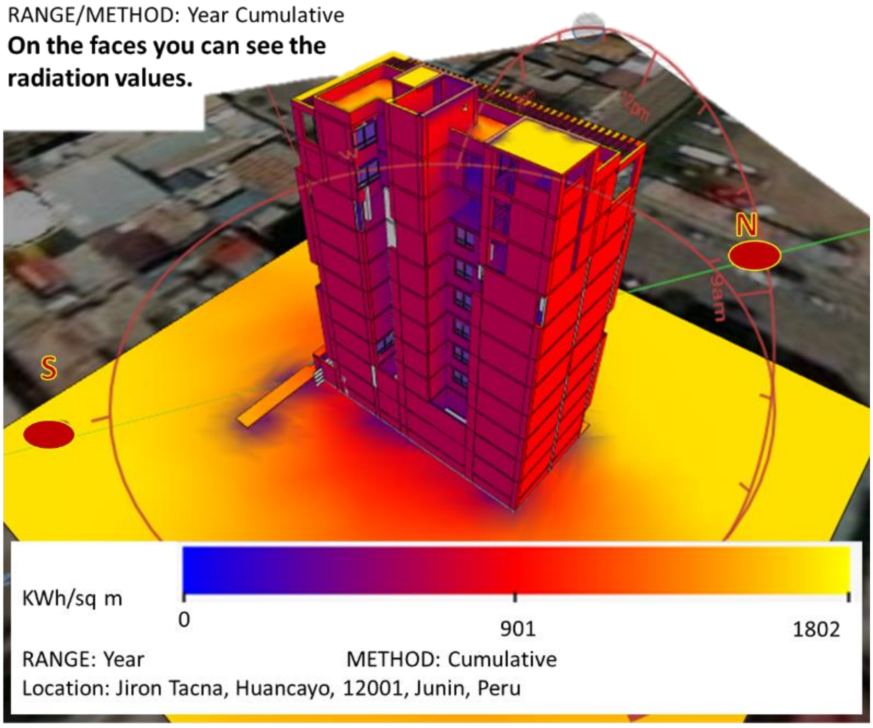


Figure 4. Solar analysis of south facade using the Formit 2024.1. program

3. Results

First, the measurement and comparison of results obtained through digital measurement were carried out, with a digital thermo hygrometer with a probe model HTC-2 of the OEM brand, in which the variation of temperatures can be differentiated, being the trend lines the blue color and its gradient, the maximum and minimum temperatures obtained outdoors during the measurement period; the yellow one, the higher and lower temperatures of the brass surface inside the house in which the measurements were made; all of this in the period from May 2024 in the city of Huancayo, belongs to the department of Jun ń in Peru (Figure 5).

According to the graph, it can be interpreted that the temperature with the use of brass tends to vary according to the external temperature, regulating all the data to a stable temperature, the projection was confirmed by applying Lagrange interpolation, which yielded the graphs that relate the external temperature to the surface without the brass cover and the external temperature to the brass cover, demonstrating that the treated variable varies so that the temperature is in the comfort range, most of the time between 8:00 a.m. and 6:00 p.m. considering temperatures between 5 ℃ and 45 ℃.

All this makes use of the Excel MS programs to generate the data of the matrix calculation and Geogebra to make the final sketch of the algebraic equations that will denote the behavior of the internal temperatures both with and without the use of brass (Figure 6).

Finally, after gathering all the data for theoretical calculations, a physical model was developed. This model includes temperature calculations, dimensioning, material selection, and comfort temperature standards according to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), as well as electromechanical design considerations. The resulting model is as follows, where pairs of points such as: (A;G), (B;H), (C;I), (D;J), (E;K) and (F;L) share the same value on the axis " x" which represents the external temperature, but on the "y" axis it varies depending on whether the skin facade is used or not, because the latter represents the internal temperature of the building.

The concept of the design was based on the decorative triangular pattern used in the Inca ceramics that came from the Mantaro Valley [19], as can be seen on page 226 of the thesis "Early Peruvian Peasants: The Culture History of a Central Highlands valley" by David Ludwig to obtain the degree of Doctor; finally, the complementary current of influence was the "lliclla" (woven mantle) which are typical cloaks of the high Andean regions of Peru, used both in ancient times and today; in most cases, they are used by women to carry their babies, various objects and food; In addition, they have different geometric shapes that were considered within Inca iconography, as well as motifs of artistic representations in their ornamental objects [20].

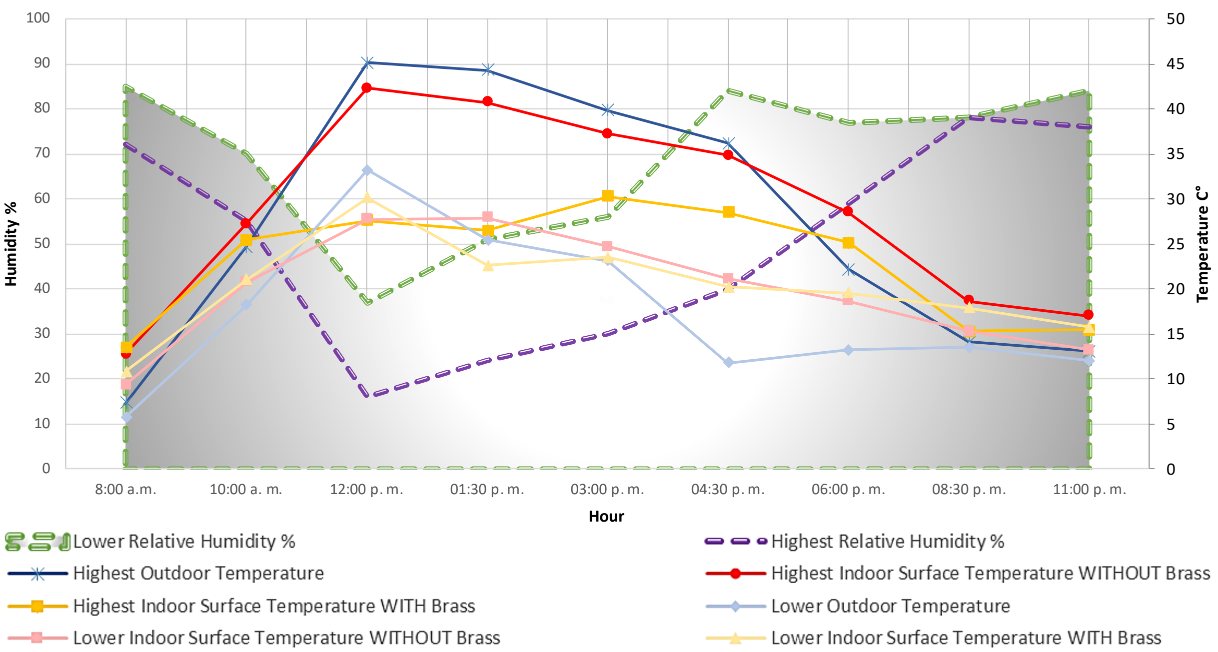


Figure 5. Compilation of temperature and humidity measurement data using or not using the modular membrane, using the Excel MS program

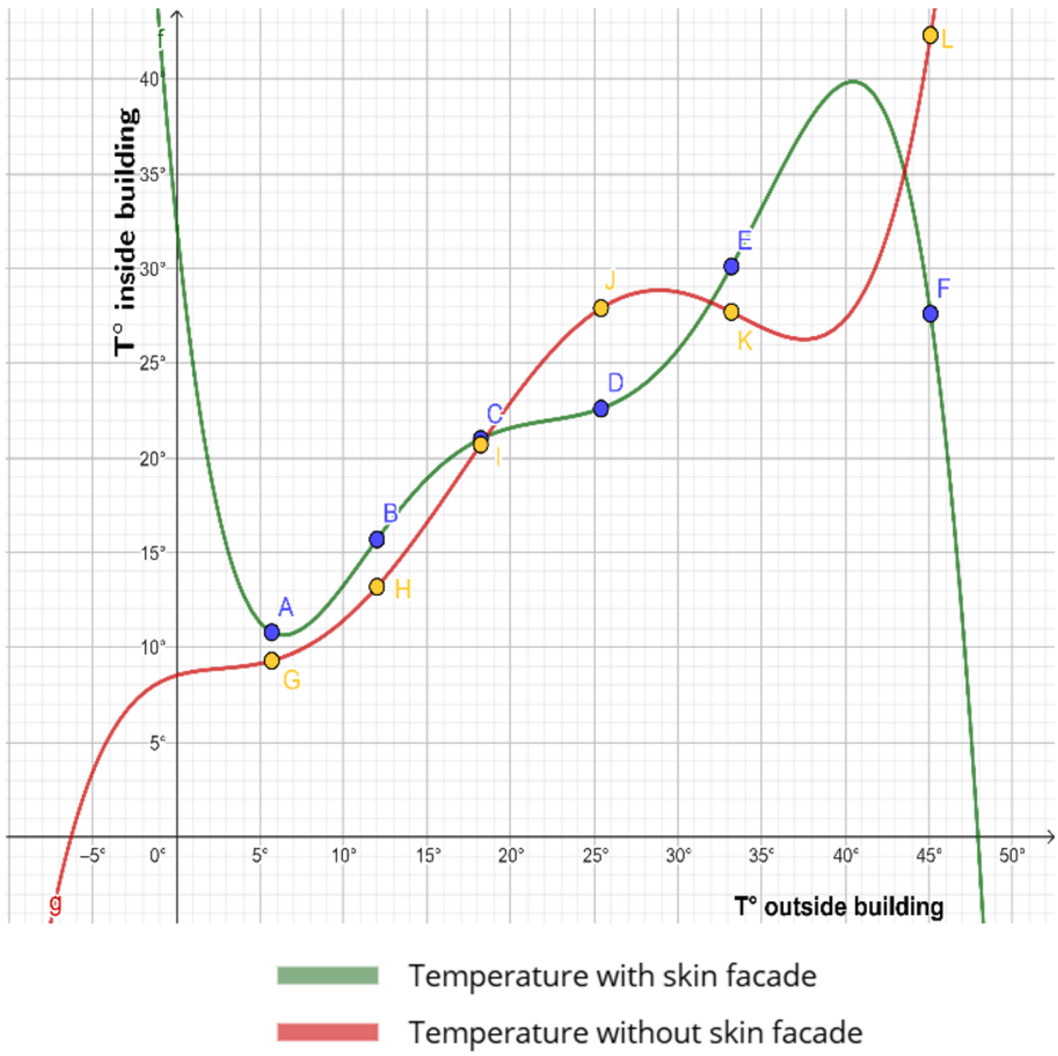


Figure 6. Comparison of predictive algebraic functions, inner T °with membrane vs. outer T °and inner T °without membrane vs. external T °

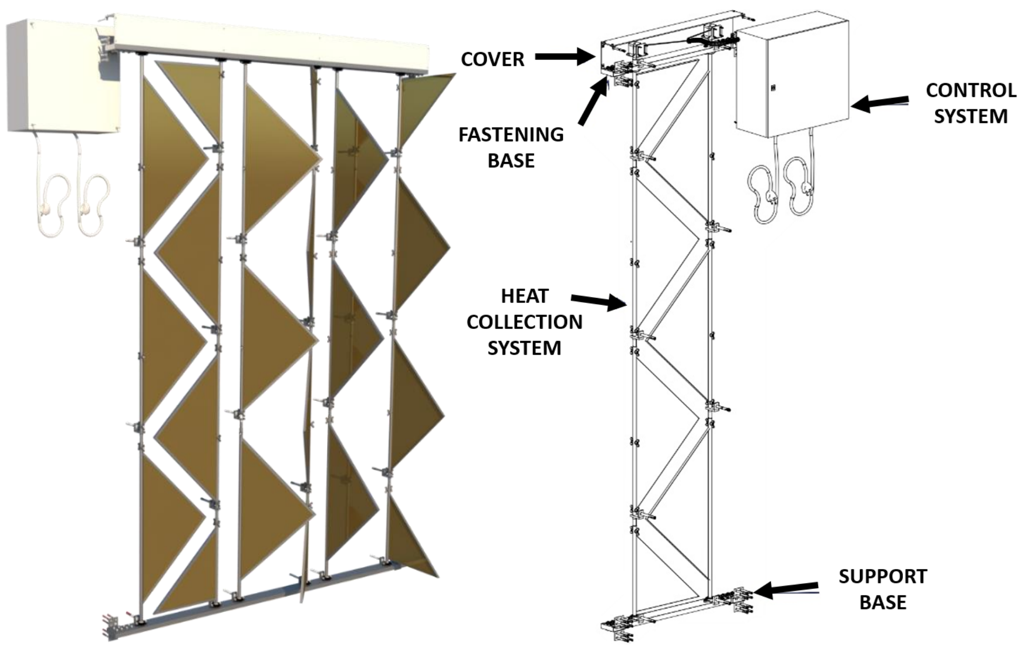


Figure 7. 3D Modeling of the Modular Architectural Membrane

The model consists of a "C" type clamping base, attached and parallel to the support base, attached both at the top and bottom to the heat collection system, all composed of multiple assembly parts, as well as an electric control system and a cover for the protection of the externally located control system (Figure 7). Specifically it is designed to meet the minimal conditions for the fulfillment of SDG 9 (industry, innovation, and infrastructure), which is the development of construction technology that positively influences the current infrastructure [21]. SDG 11 (sustainable cities and communities) specifically complies with subsection 11.4 (redouble efforts to protect and safeguard the world's cultural and natural heritage) due to the shape of the lliclla" and geometric arrangements similar to Inca pottery. Finally, SDG 13 (adopts urgent measures to combat climate change and its effects) is partially implemented because only subsection 13.2 (incorporates measures related to climate change into national policies, strategies, and plans) is supported.

4. Discussions

According to Givoni's bioclimatic diagram obtained with Climate Consultant software (Figure 8), design guidelines were provided in accordance with the California energy code so that all hours are comfortable in buildings for users.

- According to Givoni's graph, its results reinforce the use of architectural modular membranes during the winter period, given that Huancayo experiences significant climatic variation. During this stationary period, temperature regulation is essential to prevent health issues and create environments that do not hinder productivity.
- The system under study shows similarities in insulation between the modular architectural membrane (for the exterior of the building) and the heavy curtains (for the interior). Givoni highlights that heavy curtains are a significant contribution to interior design, helping to prevent heat loss at night and overheating during the day.
- The calculated parameters are highly controllable if they remain within the highest and lowest points of the graph corresponding to the Lagrange analysis. Data outside these parameters are considered non-controllable or non-measurable, which means the system's behavior in response to such data is unknown.
- For buildings with facades that include cantilevers, it is recommended to use a mobile axis system to achieve optimal heat capture, resulting in performance comparable to a smooth facade without overhangs.

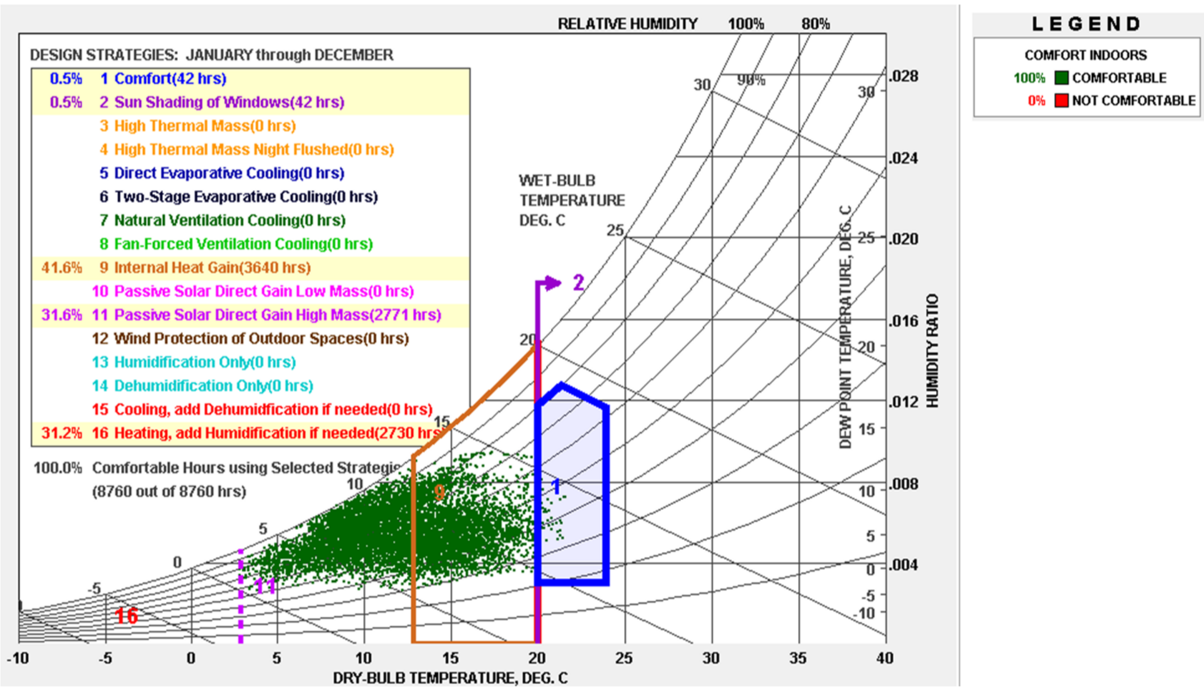


Figure 8. Givoni bioclimatic diagram using the Climate Consultant program

5. Conclusions

As for the materials used, those with high thermal conductivity, such as aluminum and stainless steel, were selected. These materials were carefully chosen not only for their ability to transfer heat efficiently, but also for their ability to reflect and store heat, which facilitates internal temperature control of the buildings without compromising structural integrity. The choice of these materials was key to the success of the project, allowing temperatures to be maintained between 20 and 24 ℃ consistently. In addition, the resulting structure is durable and energy efficient. The modular façade design, inspired by traditional Andean cultural patterns, adds value to the project by integrating cultural and aesthetic elements. This not only improves the building's energy performance, but also reinforces the cultural identity of the region, harmoniously combining tradition with technological innovation.

Specifically, brass plays a key role in this project because of its excellent ability to absorb and retain heat, making it a key material for thermal regulation in buildings. Brass has a moderate thermal conductivity, in the range of 100-150 W/m-K, which allows it to transfer heat efficiently, although not as quickly as copper or aluminium. In addition, its specific heat of approximately 0.380 J/g-℃ gives it a remarkable ability to store heat, allowing it to efficiently absorb energy during the hottest hours and release gradually as the outside temperature drops. This helps stabilize the internal temperature of buildings and optimizes energy use, reducing the need for additional heating or cooling systems. Brass, aluminium and stainless-steel form a strong, lightweight and energy-efficient composite.

Choosing these materials was key to the project's success. Each one boosts the modular facade's durability and its ability to regulate internal temperatures. Furthermore, the integration of these materials in a design inspired by traditional Andean cultural patterns not only improves the energy efficiency of the building but also reinforces the cultural identity of the region. Brass, in particular, provides a significant advantage in terms of thermal performance, the modular facade design allows for a seamless fusion of tradition and advanced technology.

Finally, physical models and digital simulations have demonstrated the effectiveness of the project. The modular façade system has improved the thermal comfort of the interiors. The optimal temperature values achieved in the project, compared to the extreme values, indicate a significant improvement in thermal regulation, with an average percentage variation of approximately -2.34%, suggesting that the internal temperature values remain more stable and comfortable. This value is beneficial in the internal thermal control of a building, helping to maintain a more balanced temperature and reducing the need for additional heating or cooling systems. This modular approach allows the system to be applied to many building projects. It benefits both new and existing buildings with thermal and aesthetic improvements. Ultimately, the project ensures thermal functionality and contributes to sustainable development by promoting more efficient infrastructures and more environmentally friendly cities. This meets long-term sustainability goals and improves the quality of life for residents.

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