HS

Revista Hábitat Sustentable

ISSN 0719 - 0700
Vol. 10 N°. 2
diciembre
2020

UNIVERSIDAD DEL BIO BIO

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Revista
Hábitat
Sustentable

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HS REVISTA HÁBITAT SUSTENTABLE V10N2
Revista del Departamento Diseño y Teoría de la Arquitectura
Universidad del Bío-Bío, Concepción, Chile

ISSN 0719-6466 versión online

DIRECCIÓN:
Avda. Collao 1202
CP: 4081112. Concepción, Chile
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Revista **HS** indexada en Scopus, SciELO, ERIHPLUS, Emerging Source Citation Index de Clarivate Analytics, Latindex Catálogo 2.0, Avery Index, DOAJ, Dialnet, Redib, EBSCO, Rebiun, JornalTOcs y ARLA.
HS se adhiere a la Declaración de San Francisco Sobre la Evaluación de la Investigación (DORA).

Revista Hábitat Sustentable es editada por el Facultad de Arquitecturas Construcción y Diseño de la Universidad del Bío-Bío, es financiada por el Fondo de Publicaciones Periódicas de la Vicerrectoría Académica, la Dirección General de Investigación, Desarrollo e Innovación y la Dirección de Postgrado de la Universidad del Bío-Bío junto al Programa de Información Científica Concurso Fondos de Publicación de Revistas Científicas 2018 Proyecto Código: FP180007

PATIO DE EDIFICIO DE VIVIENDAS EN CALLE LUMBRERAS, 24, SEVILLA (ESPAÑA).

El patio siempre ha sido un espacio arquitectónico que ha facilitado, en su entorno, la organización de la vivienda. En el mundo mediterráneo, las culturas árabes y la romana fueron conformando sus claves; y su tipología todavía perdura. En él, luz, aire, agua, sombra y vegetación, se conjugan creando un recinto que posibilita la integración entre lo interior y lo exterior.

En estos tiempos, en los que el uso del espacio público se ha complejizado profundamente, el patio, la terraza y la azotea se han convertido en ámbitos a los que hemos vuelto nuestra mirada, redescubriéndolos.

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Revista Hábitat Sustentable Vol. 10, N°. 2. ISSN 0719 - 0700/ Págs. 07
https://doi.org/10.22320/07190700.2020.10.02.00

EDITORIAL

I have been given the great honor of writing this Editorial, specifically for volume 10, the second issue of 2020 of the Journal, Habitat Sustentable. This is happening just as it begins its second decade and forms part of the SCOPUS index, a very important achievement for a scientific journal from the Chilean and Ibero-American sphere, one that is unique in addressing the specific topics of sustainability in architecture and the built environment. A great reason for feeling proud is the competent work that the UBB's Faculty of Architecture HS editorial team, involved in this process, has done up until now, where undoubtedly the community of authors, revisors and readers, who make the journal's sustainability over time possible, also play an extremely important role. From this bench, then, and with this new motivation, we invite you all to continue sending your works to HS.

The Editor responsible for HS, Claudia Muñoz PhD, started the last issue, talking about the pandemic caused by SARS-CoV-2 and wrote "on day 104 of the lockdown in Chile…". Today, it has been around 270 days since the virus' arrival in our country, the uncertainty continues and with it the tiredness, we have all accumulated with this experience, is added, which in many cases has been extremely traumatic. I cannot leave it out, given the importance and urgency scientific research of excellence in the world has garnered, and the role that, as a result, researchers and the publishing of their work play when it comes to contributing to our societies and our planet, ultimately, to save lives and positively affect the quality of life of all the species that live on Earth.

The generation of knowledge through scientific research is one that will contribute to achieving that so yearned and necessary freedom, that will let us live without fear and in a more sustainable, healthy, fair and dignified habitat for one and all. Likewise, in the academic setting, it is overwhelming to see the ploriferation of studies, reports, analyses, prospective research, surveys, etc., about what the world can entail, with respect to the fragility of our existence as a human species and the vulnerable system of life that we have developed as a society. However, beginning this new decade, having finished this year with the great pandemic we are experiencing, imposes today, more than ever, the great challenge of developing research work together, collaborating with players from the public, productive and academic sectors, hopefully more connected with the reality we live in.

This is how, from the editorial approach of HS, it is paramount to continue generating scientific-technological contributions towards the sustainability of the built environment, such as those from Argentina, Spain and Chile, in the articles here presented, where green facades or ventilated facades are seen, once more, corroborated as strategies that contribute towards improving the living conditions of occupants; or where it is likewise shown, that the ancestral and sustainable use of the land in its "earth block" version, continues being a valid construction material, technologically perfectible and one worthy of innovating starting from its qualities. To these the revision and reflection about what is on the horizon are added, "Zero Energy Buildings", and about the energy transition required to adapt to the climatic and social changes we sense daily, where it is so timely to look back at topics like the prefabrication of the past, to help us look towards the future.

Finally, looking at that horizon, I would like to thank each member of this tremendous editorial team of HS, without exception.

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Revista Hábitat Sustentable Vol. 10, N°. 2. ISSN 0719 - 0700 / Págs. 8 -23
https://doi.org/10.22320/07190700.2020.10.02.01

PREFABRICATED BUILDINGS IN CHILE: ENERGY DIAGNOSIS, 40 YEARS AFTER THEIR CONSTRUCTION. CASE STUDY: KPD BUILDINGS, SANTIAGO DE CHILE.

Recibido 29/08/2020
Aceptado 16/12/2020

EDIFICIOS PREFABRICADOS EN CHILE: DIAGNÓSTICO ENERGÉTICO A 40 AÑOS DE SU CONSTRUCCIÓN. CASO DE ESTUDIO: EDIFICIOS KPD, SANTIAGO DE CHILE.

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RESUMEN

Los edificios KPD son construcciones habitacionales sencillas y discretas, pero emblemáticas en Chile. Su recorrido histórico por este país inicia con un terremoto y se entrelaza con los antagónicos gobiernos de Salvador Allende y Augusto Pinochet. Estas construcciones han permanecido ajenas a las actualizaciones de la reglamentación térmica, pasando a formar parte del extenso parque habitacional construido que necesita ser diagnosticado energéticamente, para alinearlo a las exigencias térmicas nacionales y, de ese modo, mejorar la calidad de vida de sus habitantes y aportar a la carbono-neutralidad ya comprometida por Chile. Este artículo presenta un estudio de caso de evaluación de confort térmico en un conjunto habitacional de edificios KPD, ubicado en la Región Metropolitana. En concreto, se analizan cuatro edificios, idénticos en materialidad y distribución, pero con diferentes orientaciones. La metodología de evaluación consideró un triple enfoque: normativo, de etiquetado y subjetivo; e involucra a los habitantes en el diagnóstico, quienes constante e inexplicablemente, han quedado marginados en el análisis de sus propias viviendas. Los resultados del estudio han evidenciado discrepancias entre la percepción de los residentes y el rango de confort que utiliza la calificación energética nacional vigente.

Palabras clave
confort térmico, etiquetado energético, vivienda social

ABSTRACT

KPD residential buildings, although simple and discrete, are emblematic of Chile. Their story in this country starts with an earthquake and is intertwined with the antagonistic governments of Salvador Allende and Augusto Pinochet. These buildings have remained outside current thermal regulations, and have become part of an extensive built housing stock that need to be diagnosed in terms of energy, to align them with domestic thermal requirements and, in this way, improve the quality of life of their inhabitants and contribute to what Chile has already committed to in terms of carbon neutrality. This article presents a thermal comfort evaluation case study of a KPD residential building complex in the Metropolitan Region. Concretely, four buildings are analyzed, each with the same materials and distribution, but with different orientations. The evaluation methodology considered a three-fold approach: regulatory, labeling and subjective and involved their inhabitants in the diagnosis, who had constantly and inexplicably been marginalized in previous analyses of their own homes. The results show discrepancies between the residents' perception and the comfort range used by the current energy rating system in Chile.

Keywords
thermal comfort, energy labeling, social housing

INTRODUCTION

The history of KPD in Chile begins on July 8th 1971, during the government of President Salvador Allende, the day the country was hit by a 7.7 earthquake on the Richter scale that destroyed more than 20,000 dwellings. As a result, the former Soviet Union donated to the country a prefabricated concrete panel plant, including machinery and technical support. The factory was set up in Quilpué and was called K.P.D. (KrupnoPanelnoyde Domostroyenie) which means "Large Concrete Panel" in Russian.

The Russian technicians worked in the startup and training of Chilean workers, as such "from a technical point of view, the plant constituted for Chile a unique experience on being an advanced heavy prefabrication that incorporated new production and assembly technologies with a high percentage of mechanization and automation (Bravo Heitmann, 1996, p. 14).

In this way, KPD became the largest heavy prefabricated housing industry in the country, capable of producing 2,000 dwellings a year, as the concrete panels integrated all the ducts and anchoring points within their components for their onsite assembly.

When the Coup d'état took place in 1973, the plant was raided, the Soviet technicians were deported and Chilean staff, fired. The latter were later rehired, as they were the only ones trained to make the factory work, which was renamed VEP, Viviendas Económicas Prefabricadas El Belloto (or El Belloto Economic Prefabricated Dwellings), working until 1981. In total, 153 apartment buildings were built, located in Viña del Mar, Quilpué and Santiago (Brignardello Valdivia, 2017).

On the other hand, currently residential energy consumption in Chile, considering the end use that is given to energy, determines that 53% is destined for heating and air-conditioning (Technical Development Corporation, In-Data – CDT, 2019), as such it is not strange that the "Roadmap" set out by the Energy Ministry detects as a gap in the residential sector that, "The energy comfort level, mainly regarding the thermal quality experienced in buildings, is low or non-existent. Thus, due to this, energy consumption in buildings in the country is inefficient" (Ministry of Energy, Government of Chile, 2015, p. 48). The European Climate Foundation, in their latest study, suggest that, to achieve 100% decarbonation of the residential construction sector, policies are needed in five areas, the first being an improvement in the envelope of new and existing buildings (CE Delft, 2020), which is why conditioning this housing stock becomes a priority in the country agenda to comply with the agreements made in the recent COP25, where Chile voluntarily agreed to carbon neutrality by 2050 (United Nations Climate Change, 2019).

These emblematic buildings are part of the 67% of dwellings built before 2000, when Chile did not have a thermal conditioning regulation (Energy 2 Business SpA, 2020, p. 55). As such, making a diagnosis of their energy performance becomes relevant inasmuch as it contributes to show the thermal comfort problem that affects the country's social housing.

DESCRIPTION OF THE PROBLEM

A dwelling must offer the inhabitant inhabitability and indoor comfort conditions. However, this is not an isolated element, since it falls within a place, with a given climate and geography, where constructions and neighboring activities also interact and can condition our comfort and the inhabitability of said dwelling.

The description of comfort is broad and has several discrepancies. For this study, "thermal comfort" is considered as the state that describes a balance of environmental and personal factors that make a person feel satisfied and comfortable in their thermal environment (Nicol & Roaf, 2017).

Thermal comfort goes beyond mere satisfaction: the indoor temperature of a dwelling must be sufficient to protect residents from harmful effects for their health. In countries with template or cold climates, 18°C has been proposed as a safe and well balanced indoor temperature to protect the health of the general population during cold seasons (World Health Organization [WHO], 2018). This is related to what is stated by Howden-Chapman, Roebbel and Chisholm (2017), who confirm that cold homes contribute to excess winter mortality and to morbidity from respiratory and cardiovascular diseases. Other authors add mental health to this, as the combination of economic restrictions and cold and wet living conditions lead directly to physical health and stress issues, which once activated, together with anxiety and the distortion of moods, operate globally, affecting immune, cardiovascular and hormonal functions (Liddell & Guiney, 2015).

Contrary to what may appear at first glance, having cold dwellings is not exclusive to severe climates. This can be seen in the article of Daniel, Baker and Williamson (2019) contextualized in Australia, which states that, although outdoor temperatures are far from being extremely cold, indoor temperatures are found to be below standard and unsatisfactory for occupants who, most of the time, wanted higher temperatures in their home. This situation is repeated in the south of Spain, where three social multi-family dwellings built before the thermal regulations were monitored, showing similar results, with over 90% of hours outside the comfort range (Escandón, Suárez & Sendra, 2017).

As a result, there is a two-fold issue: on one hand, an elevated energy consumption to maintain comfort temperatures in deficient dwellings and, on the other, dwellings outside comfort ranges due to families living there not being able to afford this expense. Both situations have negative repercussions on society, whether generating emissions above acceptable limits, or harming the health of inhabitants, which have an impact on already overstretched health facilities.

STATE-OF-THE-ART

New housing is a constant demand. In fact, it is estimated that a billion new dwellings are needed around the world for 2025 (United Nations Human Settlements Program, UN-Habitat, 2016). This is added to the need to reduce and optimize energy consumption. It is for this reason that countries around the world have been implementing obligatory thermal regulations for several years now and numerous energy certifications abound for new homes, also incorporating passive strategies in the design, all seeking greater efficiency. Existing dwellings must also align with this scenario.

LEGAL FRAMEWORK IN CHILE

In thermal regulations matters, the General Ordinance of Urbanism and Constructions, hereinafter OGUC (Government of Chile, 1992), sets the requirements for opaque and translucent envelopes, and organizes the country into thermal zones. The zoning that OGUC refers to is a thermal zoning, based of heating-day degrees (Ministry of Housing and Urbanism [MINVU] and Construction Institute, 2006, p.8)

These requirements, indicated in Article 4.1.10 have been progressive: the first was established in 2000, where the obligation of thermal insulation in the roof was defined; then, in 2007, requirements for the rest of the envelope were incorporated, covering walls, ventilated floors and windows. In November 2015, Article 4.1.10 Bis was added, which establishes that the Atmospheric Decontamination and/or Prevention Plans prevail over the Ordinance. These plans are environmental management instruments whose purpose is to reduce contamination levels. Currently, there are 15 plans in force in Chile, 10 of which consider improvements of the thermal efficiency of dwellings, which is why their requirements go beyond those ruled by the OGUC (Ministry of Environment, 2020).

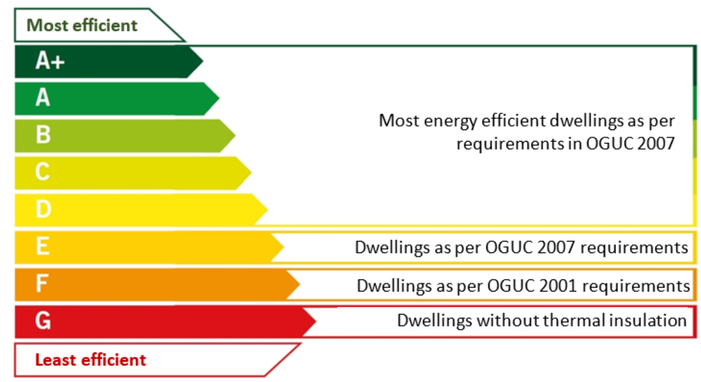

Figure 1. Figure 1. Relationship between CEV labels and the national thermal regulation.Source: Preparation by the authors based on the CEV Manual (MINVU, 2019).

As for existing dwellings and regulatory issues, the aforementioned requirements only apply for extensions, as on processing a building permit it is necessary to present to the respective municipality, the compliance accreditation form for Thermal Conditioning regulation AT-01, where the requirements to be met by the envelope considering the thermal zone and the construction solutions used for this are outlined, attaching the calculations, test certificates, datasheets and plans that apply.

DWELLING ENERGY RATING (CEV)

The Dwelling Energy Rating, hereinafter CEV, is an instrument developed by the Ministry of Housing and Urbanism together with the Ministry of Energy. It has been in force since 2012 and today is in version 2.2.

The CEV is designed for the national territory, is applicable to new and existing dwellings and defines itself as an "objective and standardized assessment that allows knowing and optimizing the energy requirement of a dwelling" (MINVU, 2019). It seeks that energy efficiency is transformed in an important factor for supply and demand in dwellings, through an attractive language for the end consumer.

The CEV issues an energy rating report and an energy efficiency label that provides, among other things, the following indicators:

- Heating consumption and demand [kWh/m^2 year],
- Cooling consumption and demand [kWh/m^2 year],
- Hours of discomfort, above and below the comfort range (HD(+-)), [h]

The labels have eight levels, from "A+" to "G", which are linked to the stages of the domestic thermal regulation, as can be seen in Figure 1.

These labels are the result of a theoretical estimation of energy requirements for heating, cooling, sanitary hot water and lighting of a dwelling in Chile. In this framework, the CEV system works with dynamic thermal balance spreadsheets called PBTD, which make a thermal balance every 60 seconds, evaluating the temperature inside the premises, based on the flows of the different entry variables.
The variables considered are:

- Internal loads: these correspond to tabulated powers.
- Radiation: climate data of the zone, which considers nearby and distant obstructions.
- Envelope: this corresponds to the heat transfer associated to this.
- Leaks: these correspond to tabulated air renewals because of leaks (RAH) (University of Bio-Bio, Construction Technologies Research Center – CITEC-UBB, Construction Direction, DECON UC 2014).
- Ventilation: air renewals per hour or ventilation rate.
- Thermal bridges: These correspond to [U] transmittance coefficients associated to different thermal bridges.
- Thermal inertia: these correspond to values tabulated for different materials.

These elements are evaluated and compared with a reference dwelling rated with the letter E, which corresponds to the current construction standard, namely, regulated following OGUC. It is important to highlight that reference demands are different for single-family and multi-family dwellings, named houses and apartments, respectively.

DESIGN V/S OPERATION

Energy certifications and thermal reconditioning of dwellings have been implemented for some time now in different parts of the world, accumulating in this way, evidence and experiences that open the door for analysis and debate.

Along this line, Ramos, Gago, Labandeira and Linares (2015) state that in the residential area, conventional energy efficiency solutions like higher standards or building regulations, are not being effective, as this sector is increasing its consumption in most countries, which can be attributed to a problem of behavior and information. Onsite evaluations are finding differences of up to 2.5 times projected energy savings, so the economic approach of energy efficiency policies, that assumes these as beneficial investments that pay for themselves, is being questioned. The engineering models on which these policies are based are being contradicted by the evidence (Fowlie, Greenstone & Wolfram, 2015), especially when the building's energy consumption after occupation differs notably from the one designed. In this sense, many ecological buildings that save less energy than expected have been seen, from which it has been suggested that a clear relationship between real energy use and the certification level of buildings cannot be seen (Geng, Ji, Wa, Lin & Zhu, 2019).

THE USER FACTOR

A dwelling is an element designed by one person, but used by another and, from this point of view, the user experience regarding the operation of said dwelling is very relevant. When collecting information, the inhabitant can really say how the dwelling works in operation. However, this is rarely sought with these purposes, leaving this out of the evaluation of their own residence. In some case studies, it has been seen that to achieve comfort conditions, this depends, to a great extent, on the willingness and capability of users, which is why there must be a correct interaction between climate, building and users that is currently not being seen (Serghides, Dimitriou, Kyprianou & Papanicolas, 2017).

The leading role of user habits in the home's energy demand is a fact, with the inefficient handling of the systems being an important source of energy wastage (Cottone, Gaglip, Lo Re & Ortolani, 2015). This is why there needs to be a transfer of operational strategies by construction professionals to the inhabitant to reduce differences between a project's design and its later evaluation on being used. In fact, there are major opportunities in terms of energy performance and satisfaction with the indoor environment in personal control (Altomonte, Schiavon & Ken, 2019). In this context, the adaptive model would obtain the greatest advantages with user interaction (Bienvenido-Huertas, Rubio-Bellido, Pérez-Fargallo and Pulido-Arcas, 2020).

The importance of including inhabitants in the energy improvements of their dwellings is seen in a case study made in Mexico, which reveals that on facing new dwellings with insulation and energy efficiency improvements compared to others without these characteristics, the estimations foreseen in consumption reduction were not reached, which was assigned to human behavior. Hence, the urgency of incorporating this factor in the models used is seen (Davis, Martínez & Taboada, 2020). Education in energy matters is complex since differences are seen in the research made in energy literacy that impede making direct comparisons and that do not end up aiding political authorities in user education issues in domestic energy conservation and management (Van den Broek, 2019).

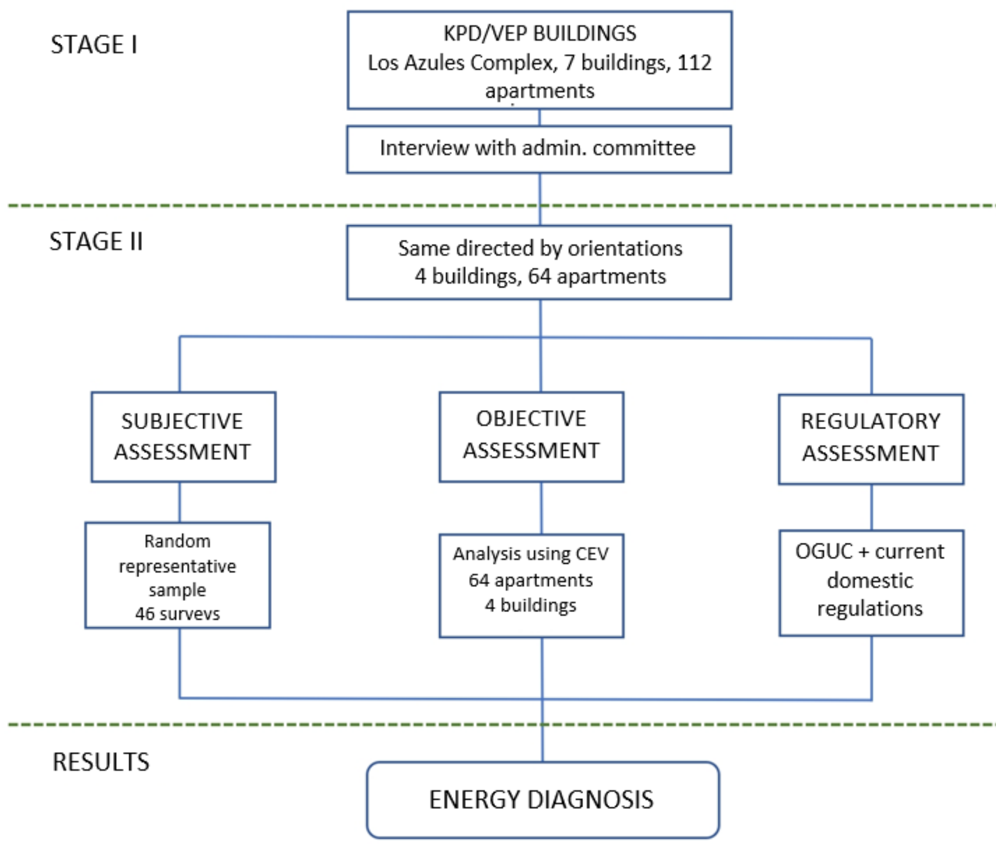

Figure 2: Diagnosis method flow chart. Source: Preparation by the authors.

It is also necessary to mention that there are discrepancies between surveys and monitoring processes, that try to write this off by a wrong location of sensors or due to temperature variations, which would cause a greater disconformity than expected (Diaz Lozano Vakalis, Touchiea, Tzekovac & Siegela, 2018).

METHODOLOGY

The diagnosis methodology, whose layout can be seen in Figure 2, considered two stages. The first stage corresponded to gathering technical information, for which a representative building was chosen, making an interview with the complex's administration committee, who provided initial information and, then, with the consultant, who provides complementary information. Once data was collected, the second stage began, which corresponded to a three-fold energy performance analysis: regulatory, which establishes the degree of compliance with OGUC and that involves checking the translucent and opaque envelope, where the current regulation to calculate transmittances is used (National Standards Institute [INN], 2007); of labeling, that uses the CEV tool and that allows evaluating the energy performance indirectly; and of perception, which makes it possible to include the inhabitants' point of view, which is relevant to show the coherence (or incoherence) of the energy rating tool's results. The thermal diagnosis of the housing complex was obtained as a result of this three-fold approach.

CASE STUDY

The complex subject of this study is called "Conjunto Los Azules". It was built in 1979 by VEP and is found in the Metropolitan region, in Santiago, in the commune of Macul.

TECHNICAL INFORMATION

LOCATION AND DISTRIBUTION

"Conjunto Los Azules" is located on Avenida Quilín, between Castillo Urizar and General Óscar Bonilla streets, in the commune of Macul in the city of Santiago de Chile and it comprises seven identical buildings. Figure 3 shows an overview of the complex.

Each building has four floors, a floor plan of 32x10 m and an approximate height of 12m, along with two staircases and four apartments per level, together totaling 16 apartments per building and 112 in total. The building's

Figure 3. Overview of the "Conjunto Los Azules" building complex. Source: Preparation by the authors based on Google Earth.

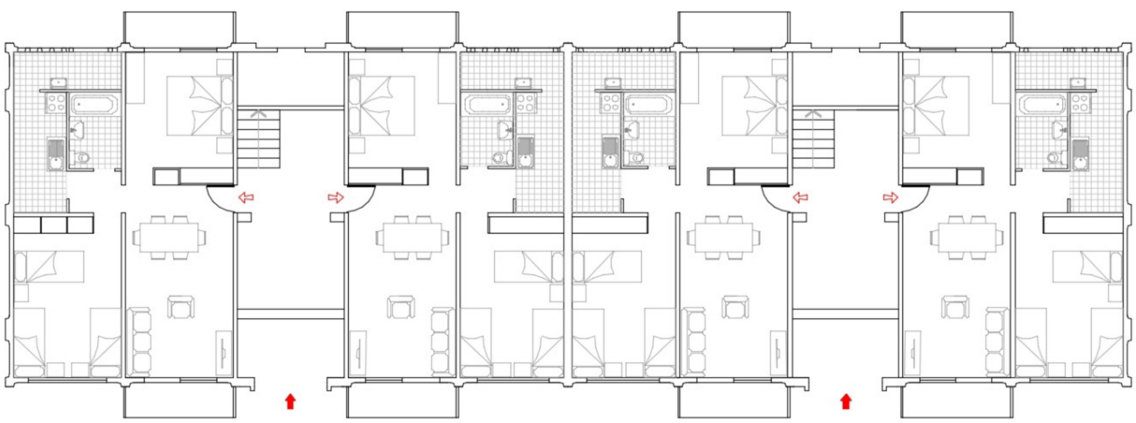

Figure 4. Distribution of the apartments, floor 1. Source: Preparation by the Authors

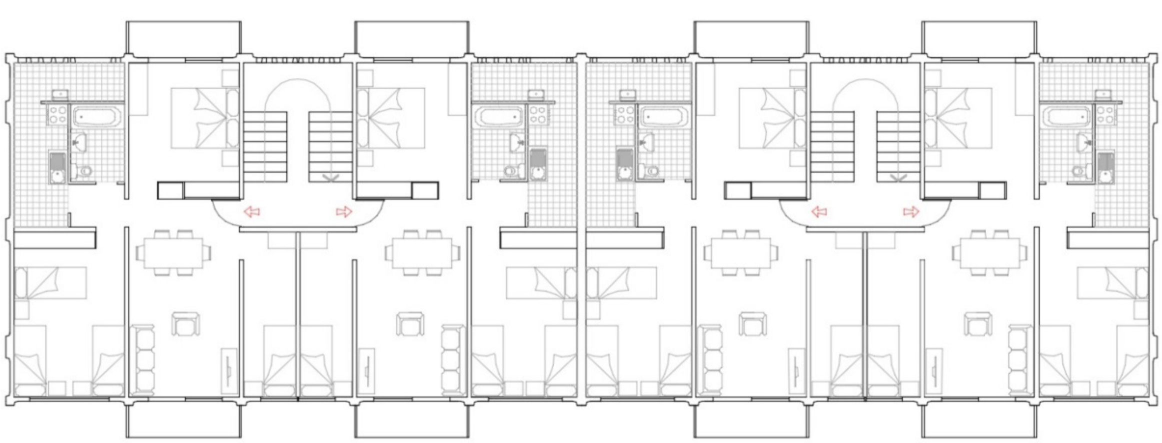

Figure 5. Distribution of the apartments, floors 2, 3 and 4.Source: Preparation by the Authors.

Revista Hábitat Sustentable Vol. 10, N°. 2. ISSN 0719 - 0700 / Págs. 8 -23
https://doi.org/10.22320/07190700.2020.10.02.01

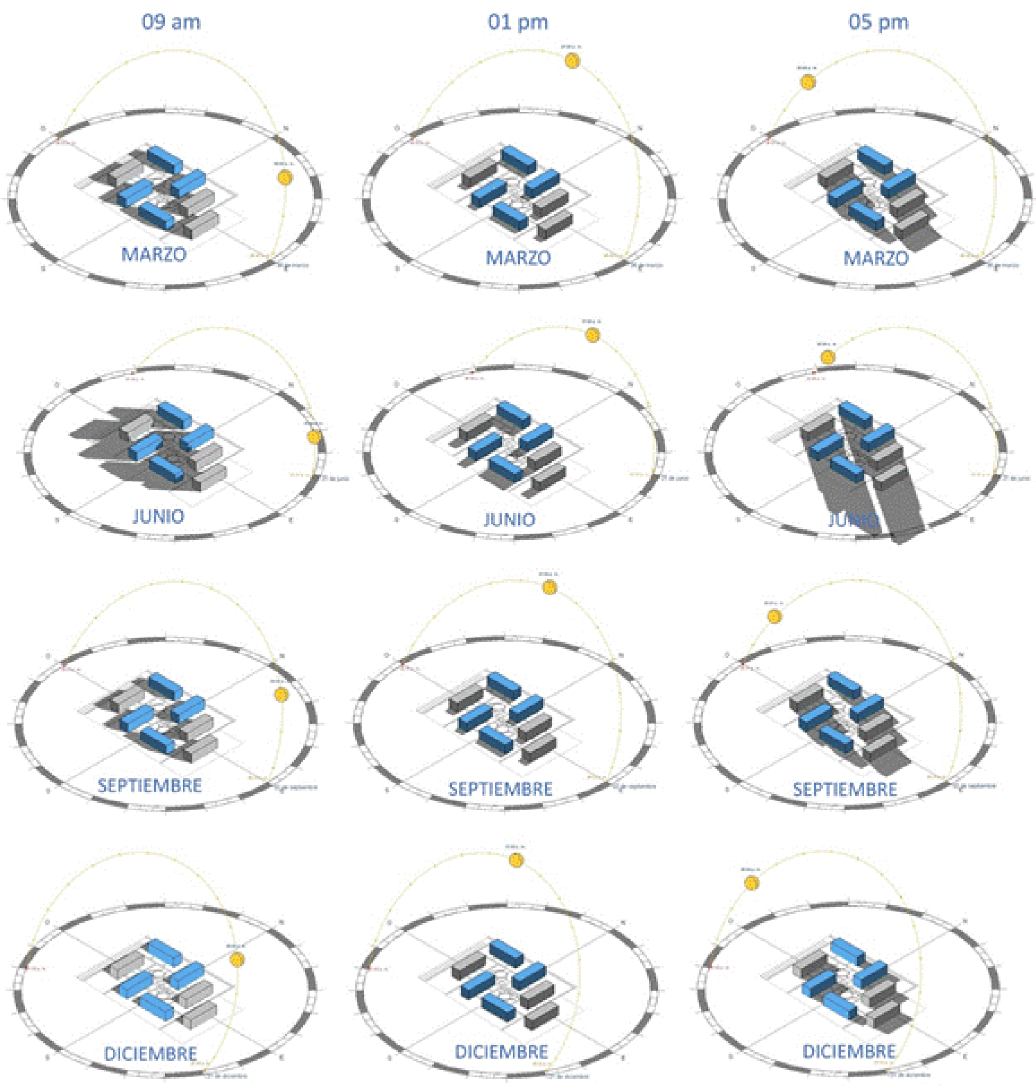

Figure 6. Solar path in the buildings analyzed, in the three times of the days and in the four seasons.Source: Preparation by the Authors.

floor plan distribution is presented in Figures 4 and 5. As can be seen, these apartments, on the first floor, are smaller as they include two bedrooms, unlike the upper floors that have three bedrooms each.

These buildings, although identical, vary in their orientation, as can be seen in Figure 3.

The study uses the façade of the dining room as the main one, on this being the one with the most exposed surface. As such, this determines the orientation of the buildings.

The orientation is, without a doubt, one of the main passive design strategies, which has an important influence on the project's cooling and heating energy demand. As an example, in this sense, from the building complex of this study, Figure 6 shows the annual solar path at three times of the day, for the four seasons of the year.

With the studied apartments being in the city of Santiago, the following was seen:

- North-facing: receives direct solar radiation during most of the day.
- South-facing: does not receive direct solar radiation most of the year.
- East-facing: receives direct solar radiation in the morning.
- West-facing: receives solar radiation during the afternoon.

It is worth noting that CEV analyzes solar radiations and possible obstructions to these, in two modalities: window accessibility factor (FAV in Spanish) that evaluates each one of them and their orientation, as well as the presence of obstructions nearby; and the accessibility factor regarding remote shading elements (FAR in Spanish), that evaluates the presence of remote obstructions for each façade. Both analyses are included in this research.

TECHNICAL SPECIFICATIONS

The data that needs to be considered for the thermal behavior study of the Prefabricated VEP Building are those corresponding to the configuration and materiality of their envelope.

- Walls: reinforced concrete prefabricated panel system. Concrete R28=200 kg/cm^2;
- Roof: 4th floor slab panels, on which structural 2" x 3" insigne pine trusses rest, with a 0.05m thick mineral wool thermal insulation;
- Floor: ventilated type. Its structure is formed by the slab panels of the 1st floor. This floor has an 8cm thick light concrete overlay;
- Windows: sliding type, with aluminum frame and monolithic glass.

RESULTS

REGULATORY APPROACH

The OGUC has requirements by thermal zone for the opaque and translucent envelope, not considering the buildings' orientation, which is why the analysis focuses on the construction typology, that is to say, not one building in particular, but rather all of them.

To check compliance of transmittances established in the opaque envelope, four methods can be chosen, which for an existing dwelling are reduced to two: test certificates of a recognized laboratory or calculation. In this study, calculations were used, made following NCh853-2007 Thermal conditioning – Thermal building envelope – Calculation of thermal transmittances and resistances (INN, 2007). In the case of the walls, three typologies were calculated, by thickness.

To check compliance of the translucent envelope, the demands vary depending on the type of glass involved, with these requirements being a maximum glazed surface percentage with respect to the envelope's vertical wall covering. This can be done using a direct calculation of surfaces or by weights; the latter are valid only in some thermal zones. Here a direct calculation was used.

The requirement for monolithic glass windows in zone 3 is 25%, a percentage that all the apartments assessed, met.

Table 1 summarizes the regulatory requirements and the situation of the complex studied.

Envelope elements	Regulatory Requirement	Situation assessed	Status
Walls	U ≤1.90 W/m2K	U = 4.70 W/m2K U = 4.11 W/m2K U = 3.68 W/m2K	Does not comply
Ventilated floors	U ≤0.70 W/m2K	U = 1.24 W/m2K	Does not comply
Roof	U ≤0.47 W/m2K	U = 0.70 W/m2K	Does not comply
Monolithic glass windows	Surface < 25% of vertical elements of the envelope	Less than 20%	Complies

Table 1. Regulatory assessment of the complex Source: Preparation by the Authors.

According to current regulation, the commune of Macul corresponds to the Central Inland (CI) climate zone, which is characterized as:

> Zone of template temperatures with moderate daytime oscillation, increasing towards the Andean foothills. High cloud cover. Intense solar radiation in summer. Short winters of 4 to 5 months. Moderate rainfall, tends to snow at higher levels (>500m). Frosts from May to August. Somewhat humid in the south. Moderate winds from S and SW (INN, 2019, p. 5).

It is worth adding that the commune of Macul does not have an Atmospheric Decontamination and/or Prevention Plan in force to improve the thermal efficiency of dwellings, hence the OGUC values were applied.

LABELING APPROACH

The CEV, unlike the regulation, does consider orientations. So, the results will be presented by orientation.

Figure 7 illustrates the location of the seven buildings. Concretely, the four orientations were analyzed and buildings 2, 3, 4 and 5 were assessed.

The CEV tool was applied to the four blocks in the study, each of which has 16 apartments. So, 64 evaluations were made.

In Figure 8, the standard façade of the buildings can be seen, which is then drawn following their different orientations for a direct reading of the labels obtained in their rating.

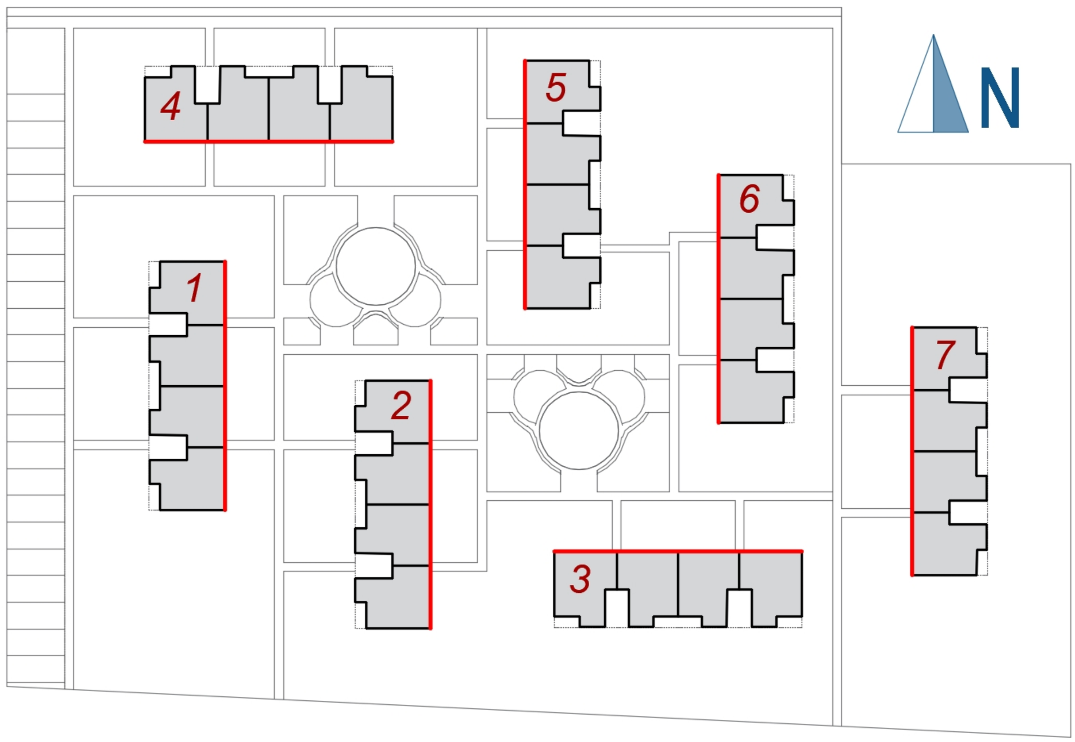

Figure 7. Orientations. Main façade outlined in red. Source: Preparation by the Authors.

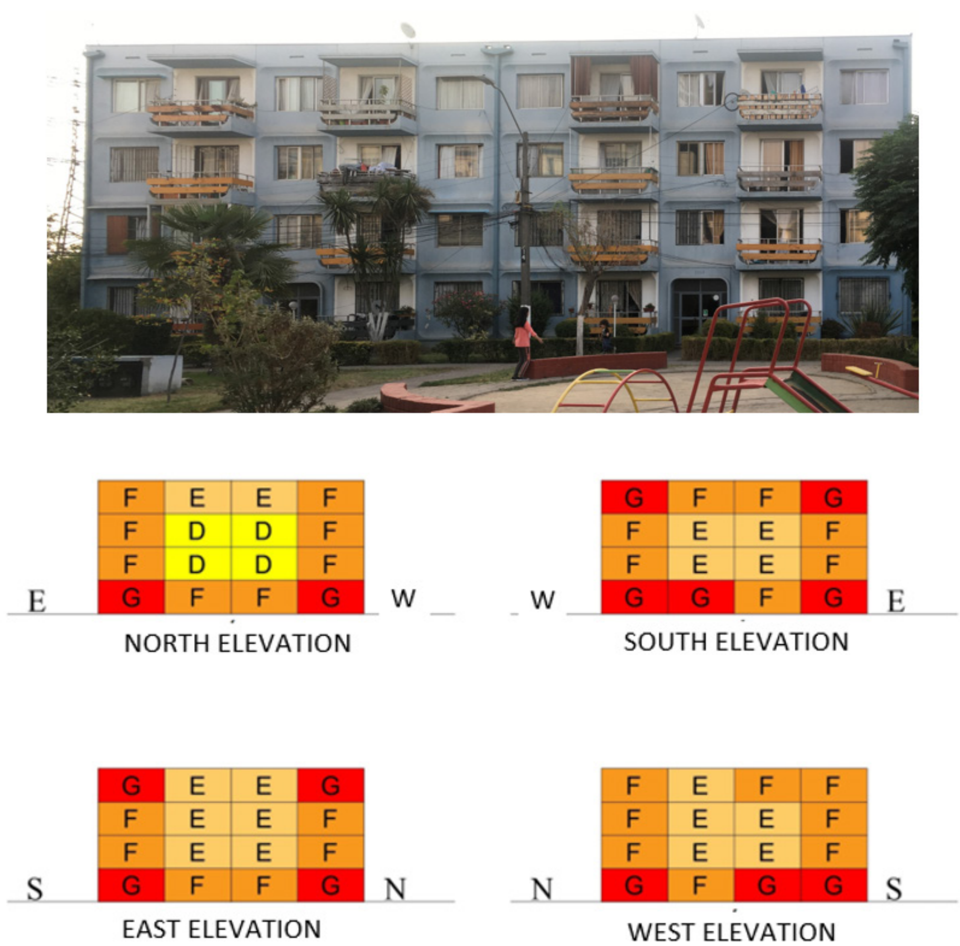

Figure 8. Ratings by orientation. Source: Preparation by the authors.

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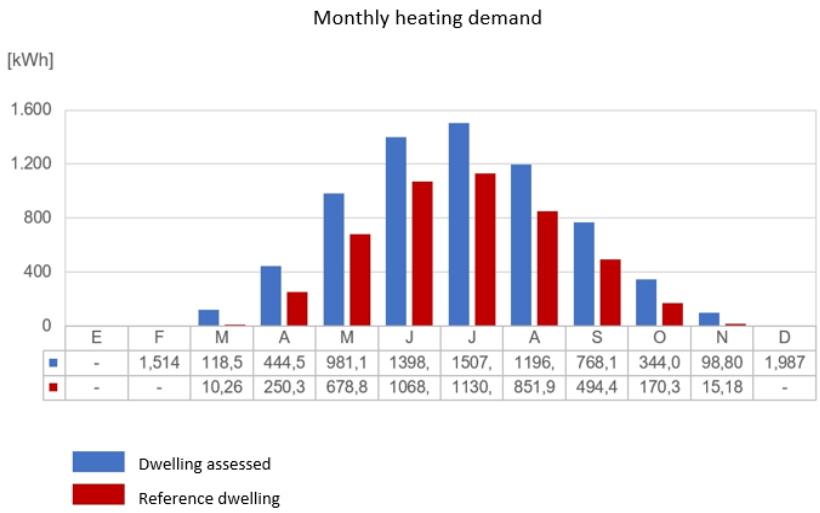
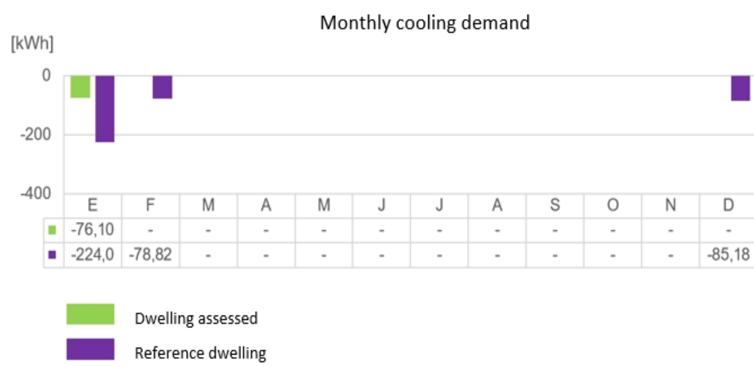
https://doi.org/10.22320/07190700.2020.10.02.01





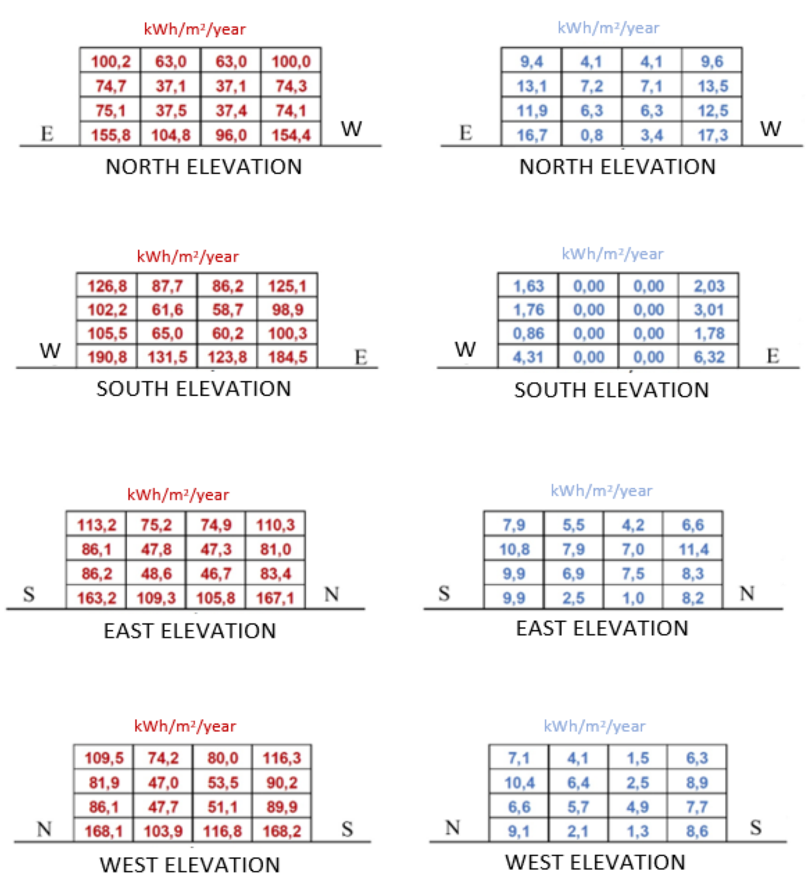


Figure 9. Monthly heating demand for one apartment Source: Preparation by the authors based on the data spreadsheet provided by CEV.
Figure 10. Monthly cooling demand for one apartment.Source: Preparation by the authors based on the data spreadsheet provided by CEV.
Figure 11. Cooling and heating demand by orientation.Source: Preparation by the authors.

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https://doi.org/10.22320/07190700.2020.10.02.01

Concept	Thermal sensation	Comfort vote	Spring	Summer	Fall	Winter
Unsatisfactory	Very Cold	-3				X
	Cold	-2				
Satisfactory	Somewhat cold	-1	X		X	
	Neutral	0				
	Somewhat hot	+1				
Unsatisfactory	Hot	+2				
	Very hot	+3		X		

Table 2. Example of answer about thermal sensation of the apartment without heating or air-conditioning Source: Preparation by the authors.

The CEV tool assigns the dwelling with a letter based on a total demand, as seen in Figure 8 and, at the same time, provides detail for heating and cooling demands, both monthly (Figure 9 and 10) and annually (Figure 11), which correspond to the results of an apartment used illustratively.

SUBJECTIVE ANALYSIS: SURVEYS

An onsite, face-to-face survey was given to inhabitants for the subjective assessment with the objective that users were the ones who state the thermal sensation of their apartment. The survey was applied to a sample population, using a confidence level of 80% and a sampling error of 5% and $p = q = 0.5$, with which a sample of 46 units resulted, which were drawn to choose the apartments.

The survey was made to the homeowners, 65% female and 35% male, respectively.

The survey asked to give a comfort vote for each season, pointing out whether the thermal sensation in the apartment is satisfactory or unsatisfactory. This is expressed in Table 2.

The results of the subjective analysis are presented in Figure 12, where they are grouped in graphs by season.

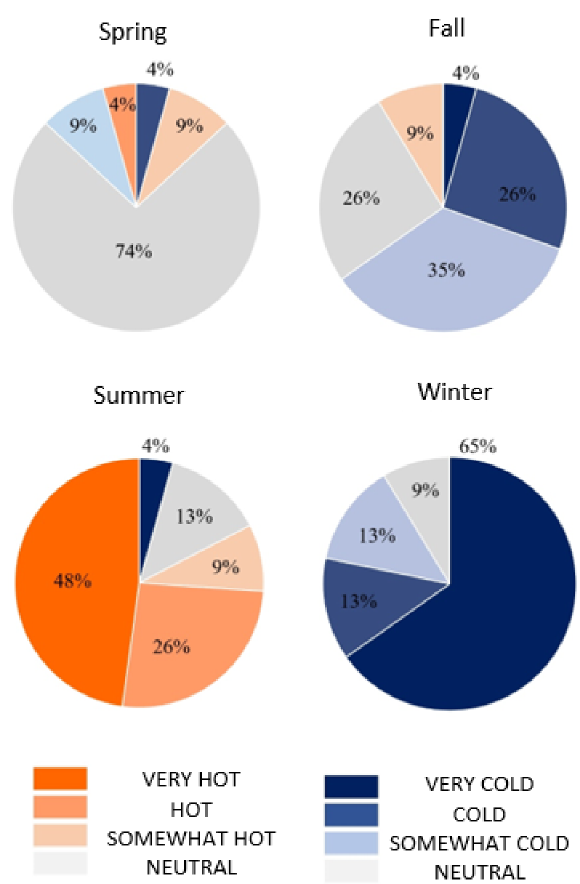

Figure 12. Comfort vote according to the dwellings' inhabitants. Source: Preparation by the authors.

ANALYSIS

As was mentioned above, the behavior of one apartment was analyzed, as an example, following the three-fold approach outlined in the diagnosis methodology used, comparing the regulations, CEV and survey, to illustrate part of the information given to us, beyond the letter.

According to CEV, the comfort range of the city of Santiago is indicated in Table 3.

The comfort temperature that the CEV considers for each thermal zone, corresponds to values determined with the method developed by Dear and Brager, adaptive model of generalized application, that determines the comfort temperature, based only on the outdoor temperature measured with a dry bulb thermometer.

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https://doi.org/10.22320/07190700.2020.10.02.01

	January	April	July	October
T° max.	26.6 °C	25.0 °C	23.6 °C	25.1 °C
T° min.	21.6 °C	20.0 °C	18.6 °C	20.1 °C

Table 3. Limit values of mean comfort temperature in °C. Thermal zone of Santiago. Values determined with Dear and Brager method.Source. Preparation by the authors based on the Procedures Manual. Chilean housing energy rating (MINVU, 2019, p. 239).

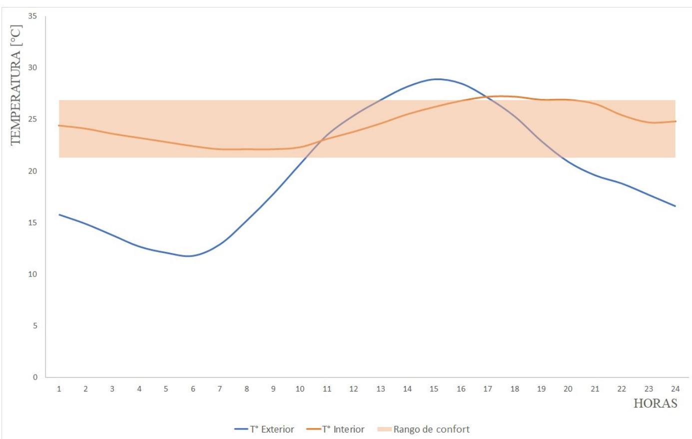

Figure 13. Representative day of January (summer). Source: Preparation by the authors based on the data spreadsheet provided by CEV.

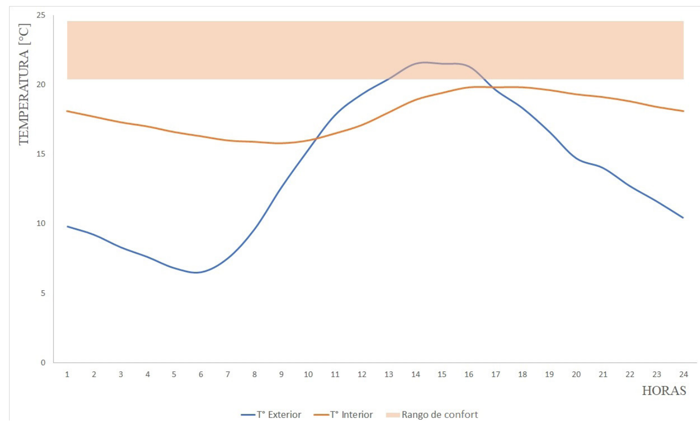

Figure 14. Representative day of April (fall). Source: Preparation by the authors

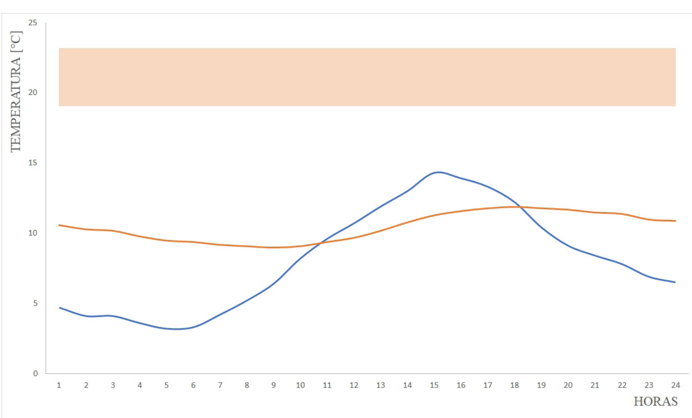

Figure 15: Representative day of July (winter).Source: Preparation by the authors.

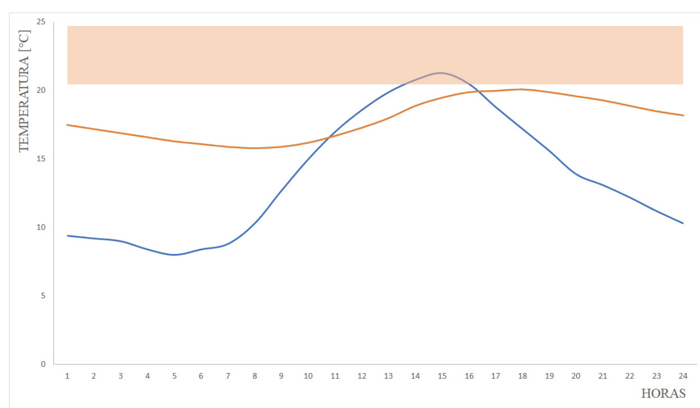

Figure 16. Representative day of October (spring). Source: Preparation by the authors.

Figures 13, 14, 15 and 16 show the temperature oscillations inside and outside one apartment, during twenty-four hours of one day, for the four seasons.

On considering this information with the survey of Table 2 (referring to the same apartment), it matches the cold sensation that is stated in winter, fall and spring. However, in January, although the temperature inside the dwelling is, according to the standard, within the comfort zone, the person surveyed states an unsatisfactory situation, as "very hot".

CONCLUSION

After having made the thermal analysis of a building from the 1970s, the fact that all these dwellings are currently outside standards is not surprising. However, what is surprising is the resignation of their inhabitants, who manifest being uninformed or disbelief on facing the possibility of improving this situation.
The study's three-fold approach, showed points where the regulation, energy rating and information provided

by the user agreed and did not do so. On one hand, despite that 100% of these dwellings were outside the standard, the CEV indicates that only 67% of the apartments are deficient regarding the current thermal regulation standard, i.e., they qualify as F or G.

On separating heating and cooling energy requirements, the CEV states that 100% of the dwellings in summer have a minimum cooling demand that ensures that the apartment is within comfort ranges, without needing air-conditioning systems, which is far from the perception of their inhabitants, who state in 83% of cases, that during the summer they are not in a thermal comfort state, but rather it was hot. However, for heating, a better agreement was seen. 91% of users state feeling cold, being effectively under the thermal comfort curve in all dwellings. Analyzing the orientations, the south-facing building, has a higher number of apartments in disconformity, as 3 out of 4 are rated with an F or G, but these are the ones that show a lower cooling demand within the complex, which agrees with the perception of the resident. This incoherence in the results is probably because the energy rating did not initially consider overheating in the assessment; and, although progress has been made in this sense, without a doubt there is still work to be done.

The study on existing dwellings presented here provided relevant information about the thermal comfort of the inhabitant, which finally allowed finding this discrepancy, which could be confirmed with direct measurements, in future research, looking to perfect the cooling demands that the tool determines.

It would be very useful that the CEV would separate the heating and cooling labels, so that the project could be easily evaluated by the buyer. Currently, there is a single label and, although there is an information breakdown, it is expressed through graphics, sometimes very specialized ones, that are beyond the understanding of an average buyer. This clearly goes against the spirit of the initiative, that was meant to approach consumers with a clear and attractive language.

There is no doubt that the iconic KPD apartments require energy retrofitting, which is now left subject to the organization of the community, or in other words, to the possibility of getting funds to do this and the amount for it. From this position, the survey is of great help since it is seen as a tool that is easily applicable, practical and accurate, and that involves residents in the evaluation process in first person, providing relevant information about family thermal comfort and involving people in the revaluation of their own home.

The organization, by the communities, is one of the main limiting factors the Ministry claims to provide funds, as such considering the participation of the dwelling's inhabitants, through the survey, that includes the aforementioned methodology, can contribute towards reducing the gap evidenced here to, ultimately reinforce the commitment of the neighbors with their surroundings and to revalue the territory.

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Revista Hábitat Sustentable Vol. 10, N°. 2. ISSN 0719 - 0700 / Págs. 24 - 41
https://doi.org/10.22320/07190700.2020.10.02.02

10 QUESTIONS ABOUT ZERO ENERGY BUILDINGS: A STATE-OF-THE-ART REVIEW

Recibido 31/08/2020
Aceptado 05/12/2020

10 PREGUNTAS DE LOS EDIFICIOS ENERGÍA CERO: REVISIÓN DEL ESTADO DEL ARTE

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RESUMEN

Los Edificios Energía Cero o ZEB (*Zero Energy Buildings*) promueven una mirada integral de la arquitectura sustentable y un cambio profundo en la manera de construir. La investigación y el desarrollo en transición energética deben necesariamente enfrentarse a problemas tecnológicos y socioeconómicos. En esa línea, la meta aquí es ofrecer una respuesta para minimizar el impacto energético y ambiental del sector edilicio. Se realizó, para ello, una revisión del estado del arte de la temática, donde se seleccionaron 97 artículos científicos considerados de mayor relevancia, en el período de 2006 a 2020. La metodología consistió en un análisis de esos textos a partir de diez preguntas formuladas para abordar la temática: sus orígenes, estado actual y proyecciones futuras en relación a la eficiencia energética y la sustentabilidad. Las preguntas hacen referencia a definiciones (P1), sustentabilidad (P2), tecnologías involucradas (P3), emisiones (P5), energía (P4) (P6) (P7), normativas (P8), cambio climático (P9) y proyecciones futuras (P10). El trabajo permite concluir que los ZEB se integran de manera holística en la transformación hacia un futuro renovable y sustentable en materia de soluciones energéticas y, a su vez, tienen potencialidad para ser implementados en diferentes posiciones geográficas y climáticas.

Palabras clave
edificios, ZEB, sustentabilidad, eficiencia energética

ABSTRACT

Zero Energy Buildings (ZEB) promote a comprehensive view of sustainable architecture and a profound change in the way to build. Research and development in energy transition must necessarily face technological and socio-economic issues. In that line, the goal here is to offer a response to minimize the building sector's energy and environmental impact. To this end, a review of the state of the art of the subject was carried out, where 97 scientific articles from a period comprising 2006 to 2020, considered the most pertinent, were selected. The methodology consisted of analyzing these texts based on ten questions formulated to address the subject: their origins, current status and future projections regarding energy efficiency and sustainability. The questions refer to definitions (Q1), sustainability (Q2), technologies involved (Q3), emissions (Q5), energy (Q4) (Q6) (Q7), regulations (Q8), climate change (Q9), and future projections (Q10). The work allows concluding that ZEB are integrated in a holistic way in the transformation towards a renewable and sustainable future in terms of energy solutions and, in turn, they have the potential to be implemented in different geographical and climatic positions.

Keywords
buildings, ZEB, sustainability, energy efficiency

Revista Hábitat Sustentable Vol. 10, N°. 2. ISSN 0719 - 0700 / Págs. 24 - 41
https://doi.org/10.22320/07190700.2020.10.02.02

INTRODUCTION

The International Panel for Climate Change or IPCC, together with the International Energy Agency or IEA, state that buildings consume 40% of international end energy and produce 33% of greenhouse gas emissions, directly or indirectly (IEA, 2008; IPCC, 2018). Likewise, it has been estimated that between 1971 and 2004, carbon emissions have increased around 2.5% per year in commercial buildings and 1.7% per year in residential buildings; a trend that continues until today (Ürge-Vorsatz, Harvey, Mirasgedis & Levine, 2007; Lausten, 2008; Zhiqiang, Zhai & Helman, 2019).

Over the last decade, Zero Energy Buildings or ZEB, also known as positive energy buildings, low energy buildings or ecological buildings, appeared, with the intention of promoting a comprehensive view of sustainable architecture and a profound change in the way to build (Marszal & Heiselberg, 2015).

The European Union in 2010, established that:

> All EU member states must ensure that by 31st December, 2020, that all new buildings are nearly Zero Energy Buildings (nZEB); and after 31st December, 2018, all new buildings occupied and owned by public authorities are nearly Zero Energy Buildings (European Commission, 2010, Art. 9 p. L 153/21)

Currently, the goal continues being reaching the global target set by the IPCC, which consists of limiting global warming to 1.5°C compared to preindustrial levels (IPCC, 2018; Kylili & Fokaides, 2015).

ZEBs promise to be an essential tool to achieve the decarbonation of the building sector (Kosai & Tan, 2017; Xing, Hanaoka, Kanamori & Masui, 2018). Their operation is based on that, through high building energy efficiency, with the use of energy production technologies with renewable sources, this is capable of equaling or, even, exceeding the consumption the building requires in an annual period (Berardi, 2018; Lung, Alberg, Connolly & Vad, 2017). This differentiates them from other buildings conceived in the framework of sustainability, as they respond to the neutral energy balance between generation and demand, limiting primary energy use (Sartori, Napolitano & Voss, 2012).

The following stand out among the most important variables to understand a ZEB: the measurement unit; the period and all types of energy included in the energy balance, along with renewable energy supply options; the connection with energy efficiency and energy efficiency infrastructure; indoor environment; and building-grid interaction (Marszal *et al.*, 2011).

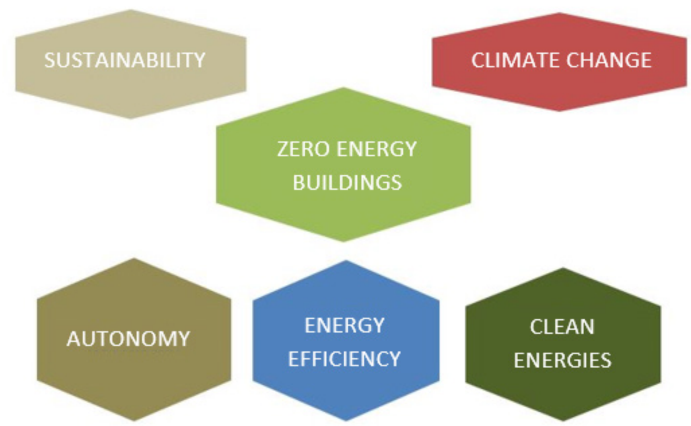

Figure 1. Topics chosen to formulate the 10 questions about ZEBs. Source: Preparation by the authors.

The goal of minimizing the building's environmental impact and carbon footprint during its life cycle demonstrates that it is important to comprehensively evaluate the building's design, since RE generation technologies also generate impacts, associated in part to their manufacturing and then, to their operation (Vares, Häkkinen, Ketomäki, Shemeikka & Jung, 2019).

As a forecast, they are presented as a growing reality towards the mitigation of emissions generated by the building sector, being key in the formation of smart cities.

The objective of this study was to make a revision of the state-of-the-art on the topic, organized starting from a format of 10 questions which were the result of 5 issues behind the literature selection: sustainability, energy efficiency, clean energies, autonomy and climate change. Starting from the answers extracted from this analytical review, we hope to make a contribution to the scientific and academic world in the debate about ZEBs.

METHODOLOGY

A revision of the specialized scientific literature published between 2006 and the present day was made, as this is the year where the issue addressed as the focus of different research appears. Two search engines were used for this: Science Direct and Google Academic. The search strategy consisted of using keywords related to the study: nZEB, ZEB, NZEB, Zero Energy Buildings, nearly zero energy buildings. In this way, more than 200 hits were obtained from the scientific and academic area, while, the references of the articles found, were also considered.

The analysis of the literature demonstrated the relationship of the topic with the following concepts: sustainability, energy efficiency, clean energies, autonomy and climate change. These guided the work

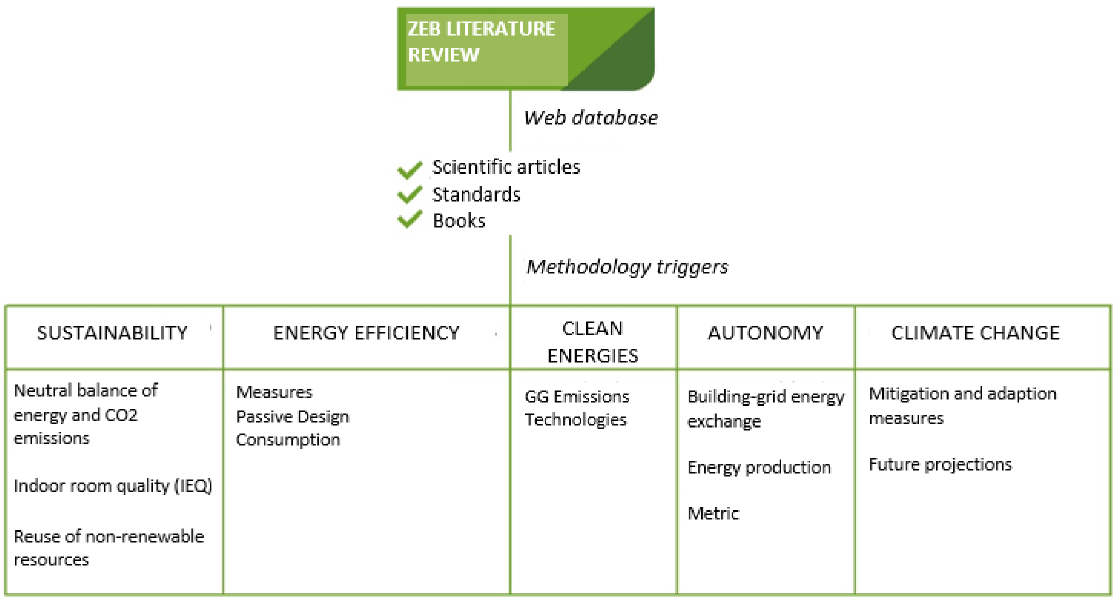

Figure 2. Study of the conceptual framework. Source: Preparation by the authors.

and, from there, created the respective conceptual framework (Figure 2). Based on these concepts, identified as intrinsic reference of the origin of the study's topic, the field of study was limited to 75 academic articles, books and book chapters. The focus of this review was answering 10 key questions, fundamental when beginning the study of Zero Energy Buildings. As a result, the literature was classified by the question it would answer (Table 1 – Appendix) and with its source: journal article, book chapter, conference article or entity document (Figure 3).

The questions (Q) were organized starting from particular topics related to ZEB to, later address more global issues such as climate change. They were organized in the following way: Q1: concept and definitions; Q2: sustainability; Q3: technologies involved in the design; Q4: building-grid relationship; Q5: greenhouse gas emissions; Q6: impact on the energy matrix; Q7: consumption of the building sector; Q8: assessment methodologies; Q9: impact on climate change; and Q10: forecasting. In this way, the conceptual framework of 10 questions for the proposed analysis appears as follows.

RESULTS AND DISCUSSION

WHAT IS UNDERSTOOD BY ZERO ENERGY BUILDINGS (ZEBS)?

There are different interpretations or guidelines about what ZEBs are, which depend on the climatic, economic or political conditions of the country that describes them, but that share a common objective: reducing or neutralizing the environmental impact of buildings (Attia, 2018).

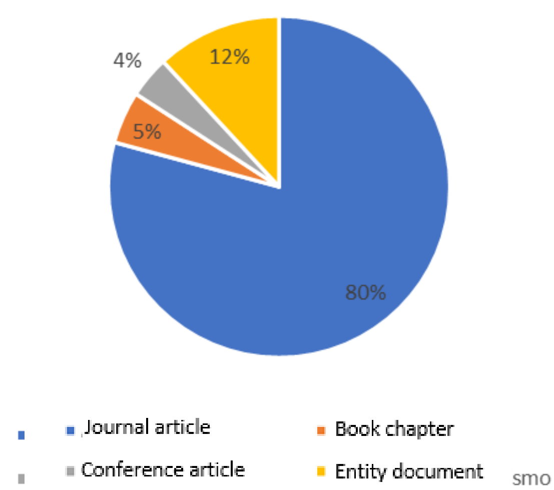

Figure 3. Origin of the sources reviewed. Source: Preparation by the authors.

The literature shows three main names: Zero Energy Buildings (ZEB), Net Zero Energy Buildings (NZEB) and nearly Zero Energy Buildings (nZEB) (D'Amanzo, Mercado & Ganem Karlen, 2019).

The nomenclature ZEB refers to a broad notion: highly technological buildings with a very low or zero energy consumption from the external distribution grid. The energy needed for their operation comes from renewable sources, in some cases exclusively, since autonomous buildings are included within this typology (Marszal & Heiselberg, 2015). They have a large proportion of this internal energy distributed, for its use in electrical appliances, heating and cooling (Carlucci, Causone, Pagliano & Pietrobon, 2017). On occasions where excess energy is produced, this can be returned to the external distribution grid or stored in batteries, in the case of autonomous buildings.

NZEB have the same characteristics as ZEB, very low energy demand and higher onsite renewable energy production (Brambilla, Salvalai, Imperadoir & Sesana, 2018). They have connection to an energy infrastructure and are characterized by their neutral energy balance, measured in a given period, normally one year, using kWh/m²/year as a numerical indicator (Booth, Barnett, Burman, Hambrick & Westby, 2010).

nZEB also have a high performance in respect to energy efficiency, since the annual primary energy consumption is very significantly covered by energy from renewable sources, either produced onsite or nearby. The primary energy value varies from 20 kWh/m²/year to 180 kWh/m²/year in residential buildings (Piderit, Vivanco, Van Moeseke & Attia, 2019). It is worth mentioning that this is the most named and mentioned denomination in the literature consulted (D'Agostino, 2016; Marszal & Heiselberg, 2015, Sartori *et al.*, 2012).

The first research on the topic emerged in the United States, in the Department of Energy (DOE), where ZEBs were defined as "buildings where you obtain enough renewable energy onsite to equal or exceed the annual energy consumption" (Crawley, Pless & Torcellini, 2009; Deru, Griffith & Torcellini, 2006). Initially, it was suggested to foster building energy efficiency through residential ZEB by 2020, and through commercial ZEB by 2025.

Meanwhile, Torcellini, Pless & Deru (2006) suggest four conceptualizations that are considered in different research projects (Congedo, Baglivo, Zacà & D'Agostino, 2015; Good, Andresen & Hestnes, 2015; Harkouss, Fardoun & Biwole, 2019; Moschetti, Brattebø & Sparrevik, 2019):

- Net zero site energy: "Building that produces the energy needed for its annual operation onsite or on the land where it is located" (Torcellini *et al.*, (2006, p.5);
- Net zero source energy: "Building that produces the energy needed for its annual operation through renewable energies, minimizing the use of external primary energy" Torcellini *et al.*, (2006, p.5);
- Net zero energy costs: "Building where energy costs for annual consumption are zero, due to the energy surplus exchange with the distribution company" Torcellini *et al.*, (2006, p.5);
- Net zero energy emissions: "Building that produces as much emission free renewable energy as it uses from energy sources that produce emissions" Torcellini *et al.*, (2006, p.5);

Figure 4. Design principles of an EEC. Source: Preparation by the authors, based on Attia (2018).

Alongside this, Kilkis (2007) highlights that it is necessary to count incorporated energy (exergy) in each stage of the building's life cycle, to establish a complete energy balance between generation and demand. Thus, he develops a new conceptual expression: Net Zero Exergy Building (ZEXB). These are buildings that have a zero total annual energy transfer, whereby the calculation counts all energy transfers that take place during a given period. Years later, Hernandez and Kenny (2010) will present a similar proposal through the term "Life Cycle Zero Energy Building" (LC-ZEB).

Directive 2010/31/EU of the European Parliament and Council of the European Union define nZEB as those in which a "nearly zero or very small amount of energy required must be covered by a significant amount of energy from renewable sources, produced onsite or nearby" (European Commission, 2010); freeing each member country to assess the amount of energy for consumption in cooling, heating, sanitary hot water and equipment, measured in kWh/m²/year.

Meanwhile, in Nordic countries, the literature presents concepts that look to holistically integrate aspects of sustainability, like the "Energy trias" (Mlecnik, 2012). Figure 4 defines ZEB through a conjunction of variables, EE with energy conservation measures, indoor environment quality (IEQ), the reduction of CO2 emissions caused by the building and the generation of renewable energies

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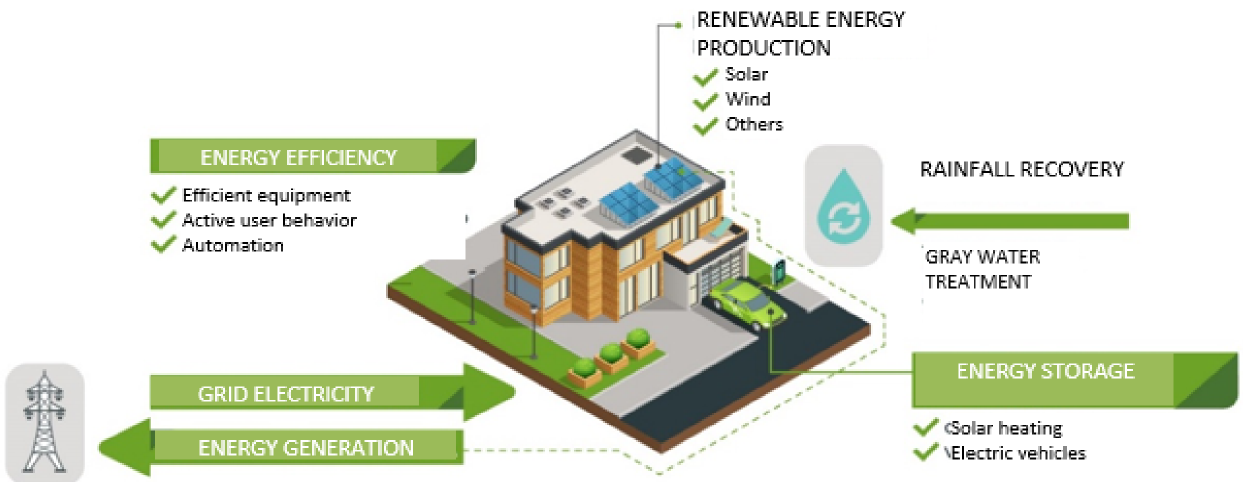

Figure 5. Integrated water and energy optimized consumption model. Source: Preparation by the authors, using Javanmard et al., 2020

(RES). According to Attia (2018), the union of these variables could determine architectonic design principles adaptable to the interests of investors.

ZEB, starting from the concepts presented, are conceived as buildings that seek energy self-supply on an annual basis and the comprehensive reduction of the environmental impact throughout their entire life cycle. Said objective could only be achieved through the incorporation of better RE technology. For this reason, nZEB are considered the first step in sites where the technology necessary for this has still not been installed. The different interpretations of the aforementioned authors establish guidelines for new research on the matter.

WHAT MAKES ZEB DIFFERENT FROM OTHER BUILDINGS CONCEIVED IN SUSTAINABILITY?

Sustainable design in architecture is a creation process where sustainable development criteria are established, such as: reduction of expenses in the natural resources used; reduction of soil, air and water contamination; improvement of comfort and quality inside the building; economic and financial savings in construction projects; and reduction of waste generated in the construction process, maintenance and end of the building's life cycle, as well as in the manufacturing of construction materials and equipment for buildings (Hernández-Moreno, 2008).

ZEB are buildings conceived from a sustainable perspective that, in addition, seek to achieve a neutral energy balance between generation and demand on an annual basis, reduce water consumption and waste, and with this, reduce the building's carbon footprint throughout its life cycle (Mertz, Raffio & Kissock, 2007; Lausten, 2008; Ibn-Mohammed, 2017; Chastas, Theodosiou, Kontoleon & Bikas, 2018; Attia, 2018).

Energy consumption is linked to comfort standards, considering sustainability in the determination of the indoor climate of buildings and preferring, as a result, available low energy solutions (Nicol & Humphreys, 2002). This statement is clear in the ZEB, where indoor thermal and visual comfort is sought, by means of energy free resources, like solar gains and natural ventilation (Kalbasi, Ruhani & Rostami, 2019; Wei, Wargocki, Zirngibl, Bendžalová & Mandin, 2020).

Several studies also present them as a solution for water consumption and the waste produced around the world by the building sector, -14% and -60% respectively, according to Petersdorff, Boermans and Harnish (2006); and the reuse of waste for new purposes and recycling (Belausteguigoitia Garaizar, Laurenz Senosiain & Gómez Telletxea, 2010; De Gisi, Casella, Notarnicola & Farina, 2016). For this reason, they are considered as a comprehensive solution to face the issue of energy consumption and environmental deterioration (Guillén-Lambea, Rodríguez-Soria & Marín, 2017; Chastas *et al.*, 2018; Piderit *et al.*, 2019; Deng, Wang & Dai, 2014). Figure 5 shows the optimal operation of a ZEB, according to Javanmard, Ghaderi & Sangari (2020).

In order to validate the behavior of a ZEB or nZEB, there must be a neutral or near zero energy balance, on an annual basis. The units for energy balance may be distributed energy, primary energy, CO_2 equivalent and exergy (D'Agostino, Marino, Minichello & Russo, 2017). Other parameters, like the metric of the balance and the balance period are defined by the regulations (Marszal *et al.*, 2011).

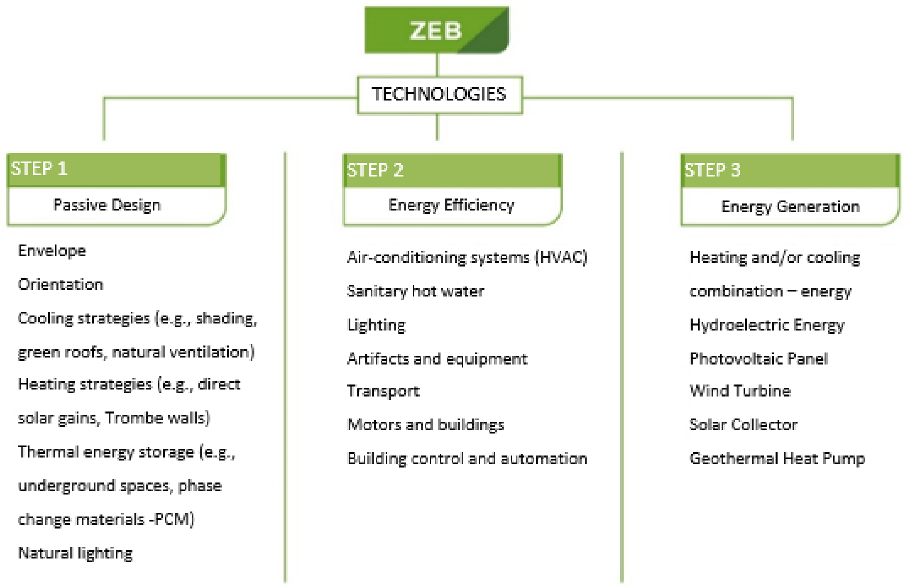

Figure 6. Technologies by categories integrated in ZEBs. Source: Preparation by the authors, using Deng et al. (2014).

Sartori *et al.* (2012) distinguish three types of balance – annual import-export (Equation 1); annual demand-generation (Equation 2), and monthly demand-generation (Equation 3).

$$\sum e \times f_e - \sum i \times f_i = E - I \geq 0 \qquad (1)$$

Where *E* and *I* correspond to exported and imported and *f* to the metric factor (kWh, kWh/m^2, CO_2, exergy, etc.)

$$\sum g \times f_g - \sum d \times f_d = G - D \geq 0 \qquad (2)$$

Where *G* and *D* correspond to generation and demand and *f* to the metric factor (kWh, kWh/m^2, CO_2, exergy, etc.)

$$g_{m,e} = \sum_m \max[0 \cdot g_e(m) - d_e(m)]$$

$$d_{m,e} = \sum_m \max[0 \cdot d_e(m) - g_e(m)]$$

$$\sum gm,e \times f_{gm,e} - \sum dm,e \times f_{dm,e} = Gm - Dm \geq 0 \qquad (3)$$

Where *Gm* and *Dm* correspond to monthly generation and demand and *f* to the metric factor (kWh, kWh/m^2, CO_2, exergy, etc.)

The choice between the three balance types will depend on the scope that is established. Generally, the annual demand and generation balance is used (Equation 2), since, according to the authors, it allows obtaining a greater number of results to analyze.

On the other hand, if one needs to know the emissions produced directly or indirectly during the processes related to the building's construction, its maintenance and end of life, the Neutral Carbon Balance can be made (Moschetti *et al.*, 2019; Seo, Passer, Zelezna & Hajek, 2016). Through the building's Life Cycle Analysis tool (Fjola *et al.*, 2018; Hernandez & Kenny, 2010; Jusselme, Rey & Andersen, 2018; Moschetti *et al.*, 2019) or through calculation formulas of tons of carbon accumulated in the building's materials and amount of emissions, as indicated by equation 4 (Rodríguez Manrique, Kobiski & Fassi Casagrande Jr, 2014).

$$E_{kg}CO_2 = \sum_{i=1}^{n} a_i \cdot b_i \cdot c_i \qquad (4)$$

Where *a* means the amount of energy accumulated by type of material (MJ.m^{-3}); *b*, the percentage energy consumption by source; *c*, the CO_2 emission by source (kgCO_2.MJ^{-1}); *i*, the typology of the material, and *n*, the amount of material.

It can be said that the road towards a carbon neutral ZEB must focus greatly on the energy incorporated in the materials and the emissions, given that the low demand of operational energy is already a priority regulated in most countries (Moschetti *et al*, 2019).

WHAT ARE THE TECHNOLOGIES INVOLVED TO ACHIEVE ZEBS?

The technologies involved to achieve ZEBs are: Passive and energy conservation technologies; Energy Efficiency in the building's operation; and technologies to produce energy from Renewable Energies (Cao, Dai & Liu, 2016).

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In step 1 (Figure 6), numerous studies are seen that deal with the envelope, promote the use of low carbon emission materials and natural ventilation to reduce the possibility of overheating inside buildings (Li, Yang & Lam, 2013; Volf *et al.,* 2018). Moga and Bucur (2018) propose the integration of nanomaterials, as these possess 3 to 5 times less conductivity, along with a reduced thickness, and they state that this could be an interesting variant in building rehabilitation cases, where the option of adding thickness to the envelope is difficult.

Regarding step 2 (Figure 6), about EE technologies, several authors encourage reusing indoor air through air exchangers for cooling and heating (Bordoloi, Sharma, Nautiyal & Goel, 2018; Justo Alonso, Liu, Mathisen, Ge & Simonson, 2015; Liu, Li, Chen, Luo & Zhang, 2019), and automation and control systems for an optimal operation (Buso, Becchio & Corgnati, 2017; Hamdy, Nguyen & Hensen, 2016).

As for step 3 (Figure 6), literature presents that the most used RE source in these buildings is solar energy, through the integration of Photovoltaic Panels for electricity, for SHW systems and thermal solar conditioning, combined with heat pump systems (Jovanovic, Sun, Stevovic & Chen, 2017; Li *et al.*, 2013; Osseweijer, Hurk, Teunissen & Van Sark, 2018). In terms of cooling systems, new technologies with desiccants and membranes are incorporated, to foster energy saving and low environmental impact (Chen & Norford, 2020).

DOES A ZEB PRODUCE ENERGY CONNECTED OR ISOLATED FROM THE GRID?

A ZEB produces renewable energy onsite for its supply and the surplus is exchanged with the external grid. When the energy generation is not enough to cover consumption needs, energy is taken from the external grid (Berardi, 2018). In cases which have energy storage batteries, the electricity for the building's operation is taken from three sources: intermittent renewables (for example, Photovoltaic Solar); energy storage battery; and external infrastructure. The sum of the energy among them is consumed by the demand sought (Kosai & Tan, 2017).

For the U.S. Department of Energy and The National Institute of Building Sciences (2015), the designation of ZEB must be used only in buildings that have demonstrated, through their current annual measurements, that the distributed energy is less than or equal to the renewable energy exported from the site.

Meanwhile, Debbarma, Sudhakar and Baredar (2017) explain that the electricity generated by integrated photovoltaic panels can satisfy approximately between 20% and 75% of electricity requirements, depending on the city and its location. The difference between the time of use and time of generation of onsite or "nearby" electricity, complicates the possibility of using all the electricity for self-consumption. The connection to the grid tends to be necessary to allow a true zero energy physical balance. Therefore, it is assumed that excess electricity generated onsite is sent back to the grid, using this as unlimited storage (Hermelink *et al*, 2013). Given what has just been said, the variant of autonomous buildings is not recommended as the generation system is oversized to reach self-consumption and a very high cost electrical and thermal energy storage system is required (Lausten, 2008).

As an example of interaction with the grid, studies made in Latin American countries show important progress in their legislation on "Distributed generation", which contributes to reaching higher ZEB integration possibilities. In this context, Vargas Gil *et al.* (2020) state that the largest photovoltaic solar plants of South America are located in Brazil and Chile, and they also highlight the renewable energies plan of Argentina (renovAR), whose objective is awarding electricity contracts using renewable sources.

Likewise, regarding distributed generation for self-consumption, Costa Rica has a recording system through the Energy Direction of the Ministry of Environment and Energy (MINAE), where an installed total of 54,504.92 kW is seen, in the framework of Decree 39220 – MINAE, to April 2020, which represents more than 1,924 registered systems (MINAE, 2015; Strategic Energy, 2020). Chile, in turn, has Law 21.118 from 2019, where the right is given to the distributer's clients to generate their own energy, self-consume it and inject their surplus to the grid under the Net Billing modality (Ministry of Energy, 2018). And Argentina has Law N°27.424, with similar conditions (Honorable Congress of the Argentine Nation, 2017).

WHAT IS THE IMPACT OF GG EMISSIONS INVOLVED IN THE GENERATION OF ENERGY USING RE, FOR THE OPERATION OF ZEBS?

Energy generation using Renewable Energies is recognized for its contribution towards the reduction of GG in the atmosphere. According to IPCC, the quick integration of EE and RE technologies in buildings will lead to a drastic reduction of CO_2 emissions (Rogelj *et al.,* 2018).

From this perspective, several works have proven that clean energy generation produces environmental impact. Hammond and Jones (2008) indicate that, on photovoltaic panels, CO_2 emissions on fine plates are 67 kg CO_2/m^2 and monocrystalline of 242 kg CO_2/m^2. According to Finnegan, Jones and Sharples (2018), the study of the life cycle analysis of new and existing technologies is essential to choose the appropriate system.

The amount of GG accumulated in ZEBs is associated to the materials and technologies installed in the building. As an example of this, the graph of Figure 7 summarizes the results of the research of Vares *et al*. (2019, where three building cases with an nZEB, without integration of RE, were compared. There, EEC1 corresponds to a building connected to the external electricity grid with the integration of thermal solar energy for SHW, PV fine plate panels and plate type thermal solar collectors; EEC2, to one that has no connection with the electricity grid and has equal RE generators with the addition of batteries to store solar energy; and, EEC3, to another that is connected to the electricity grid and generates all the energy for heating and SHW thermal solar energy using parabolic plate type collectors.

Ultimately, it is seen that, during the estimated 25-year life cycle for the systems, the greater the building's autonomy is, the accumulated emissions increase. However, when the RE technology chosen produces electricity (EEC-1 case), it generates 40% less GG emissions, in comparison to an NZEB without RE integration (Vares *et al.*, 2019).

The EEC1 variant shows that, under conditions that consider an active user in energy efficiency matters, energy conservation strategies could be combined and thus reduce the percentage of emissions during the system's operation, mainly for heating and cooling.

It can be said that the GG impact involved in ZEBs can be regulated by the decisions of the investors regarding technologies being integrated in the buildings (Attia, 2016; Azzouz, Borchers, Moreira & Mavrogianni, 2017; Hernandez & Kenny, 2010; Lamnatou, Motte, Notton, Chemisana & Cristofari, 2018).

WHAT IS OR WHAT WOULD BE THE IMPACT ON THE ENERGY MATRIX?

ZEB are integrated holistically in Smart Energy Systems, in the electricity, heating, cooling, industry, buildings and transportation sectors, to address solutions for a transformation towards a renewable and sustainable future in energy solutions (Lund *et al.*, 2017).

Along this line, Seljom, Byskov, Tomasgard, Doorman & Sartori (2017) made an analysis about the impact of these buildings on the reduction of energy

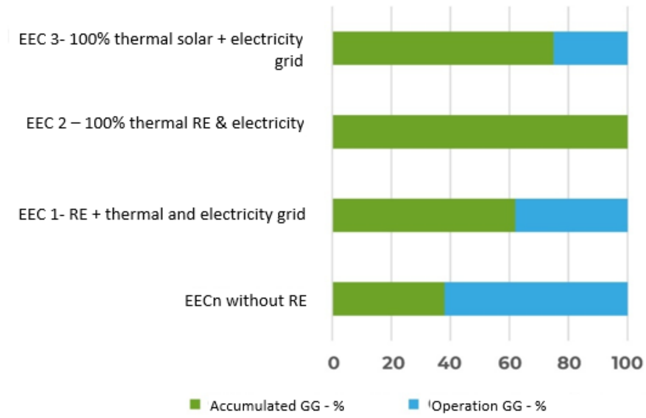

Figure 7. Comparative graph of the percentage of GG emissions for 25 years of operation for each case. Source: Preparation by the authors, using Vares et al. (2019).

consumption with projections to 2030 and 2050 for the Scandinavian system. The results revealed a reduction of electricity consumption for heating of 8% and 18%, respectively. Bearing in mind that a 25% renewal of all building stock in ZEB is expected by 2030, and 50% by 2050, this would change the operation of flexible electricity generation.

District Heating and Cooling Systems (DHC) are based on the use of local sources of heat, cooling and fuels which, under normal circumstances, would be lost. On the DHC platform (2012) [1], three scenarios 2020-2030-2050 are suggested for the EU, in which it is foreseen to extend existing urban heat production plants and increase solar-thermal plants.

In Latin America, progress is being made in energy efficiency policies. In Argentina, for example, they have moved forward in building energy certification projects in the standard, IRAM 11900-2017 "Energy supply in dwellings. Calculation method and energy efficiency labeling" (IRAM, 2017), which seeks to evaluate the end use of conventional energy that contributes to the energy demand of the dwelling through heating, cooling, indoor artificial lighting and sanitary hot water services. The design bioenvironmental strategies are mentioned as an effective way to contribute towards EE (Fernández, Garzón & Elsinger, 2020).

In terms of RE generation, law N°27.424 is ratified in Decree 1075/2017 "System to encourage the distributed generation of Renewable Energy integrated to the public electricity grid" (Honorable Congress of the Argentine Nation, 2017), where the legal and contractual conditions are established for the generation of electricity of a renewable origin

1 See https://www.euroheat.org/publications/brochures/district-heating-cooling-vision-towards-2020-2030-2050/

by users of the distribution grid. An important step is considered in the Argentine national legislation that starts ZEB integration. Specifically, article 7 indicates that:

> starting from the ratification of this decree, all domestic public building construction projects must consider the use of a distributed generation system from renewable sources, consistent with taking advantage of the zone it is located in, prior study of its environmental impact where this applies, pursuant to the applicable regulations in the respective jurisdiction. (Honorable Congress of the Argentine Nation, 2017, p. 4).

WHAT IMPACT DO ZEBS HAVE ON THE CONSUMPTION OF THE BUILDING SECTOR?

ZEB could make important savings in the sector's consumption. In fact, an energy demand of 25% to 50% lower than that generated by conventional buildings is estimated (Häkämies *et al.*, 2015). For this, it is worth highlighting that it is necessary to underline an efficient user behavior in the use of passive systems and active technologies (Carpino, Mora, Arcuri & De Simone, 2017; Causone, Tatti, Pietrobon, Zanghirella & Pagliano, 2019).

In Figure 8, the different sectors included in balance calculations are illustrated, and it is seen that the highest potential in energy savings is found in the reduction of the heating and cooling demand (Garde *et al.*, 2014). A building in template climates, with a suitable insulation, could reduce heating demand by between 20% and 50% (Taleghani, Tenpierik, Kurvers & Van den Dobbelsteen, 2013). To achieve an optimal design, the consumption should be 30 kWh/m^2/year (Hermelink *et al.*, 2013). D'Agostino and Parker (2020) also consider that it is important to reduce the impact of the energy consumption coming from lighting and household appliances.

In Figure 9, an example of the operation and calculation of the energy flows within a ZEB is seen, where concentric scales show, from outside in, the building's interaction with the external grid. First of all, the net primary energy enters to cover thermal and electrical demand until reaching the limit with the external grid system. The building takes the energy needed for different sectors' consumption and covers the whole demand with energy generated from RE systems. Finally, the surplus is exported to the distribution system, generating a positive balance between generation and demand.

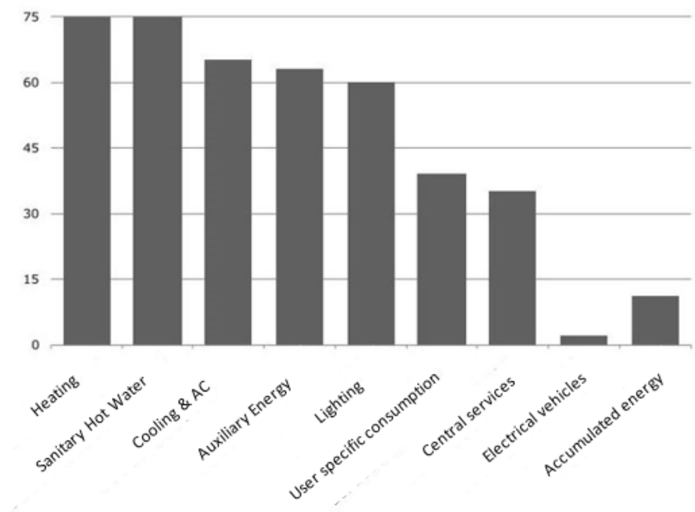

Figure 8. Demand by sectors included in the calculation of the balance for a ZEB. Source. Hermelink et al. (2013).

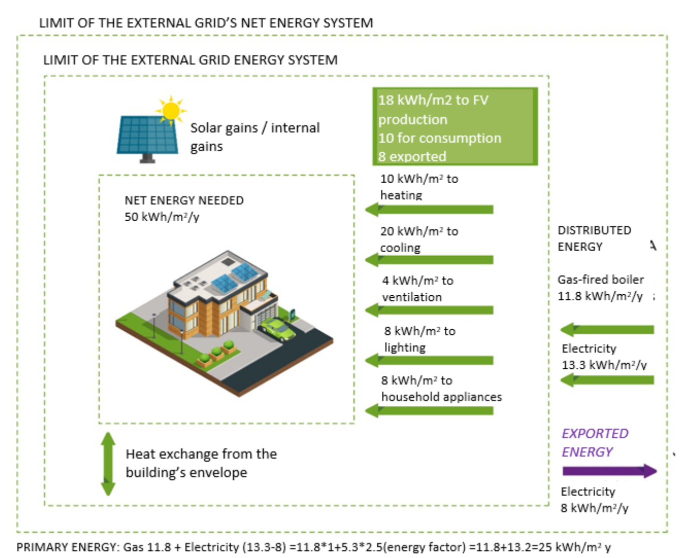

Figure 9. Example of the calculation of energy flows in a ZEB. Source: Preparation by the authors, using Berardi (2018).

ARE THERE METHODOLOGIES TO EVALUATE A ZEB?

The concept of ZEB requires a clear and consistent methodology for energy calculations. Initially, the most important unknowns in this sense were about the measurement of the balance, the period of the balance, the type of energy included in the balance, the type of energy balance, accepting renewable energy sources, the connection with the energy infrastructure and the requirements to achieve energy efficiency, indoor climate and, in the case of

Figure 10. Vision of EEC as regenerative and sustainable buildings. Source: Preparation by the authors, using Attia (2016).

buildings with a connection to the grid, interaction of the building with it (Marszal *et al.* 2011).

As a reference to determine a regulatory framework, the literature highlights two main legislations: that passed by the Directive of the European Parliament and Council (EPBD), in regulation 2010/31/EU from 2010 and that established by the Department of Energy of the United States (US DOE) "*A Common Definition for Zero Energy Buildings*" from 2015. In the first, it is indicated that public buildings built until 31/12/18 must be nZEB and, consequently, all buildings being built to 31/12/2020 will be (European Commission, 2010; D'Agostino, 2016; Pacheco-Torgal, 2014). The second defines as a main strategy, reaching sellable ZEB dwellings by 2020 and commercial buildings by 2025.

Years later, the contribution of IEA along with SHC (Solar Heating and Cooling) through the Task 40 program – Energy conservation in community buildings and systems (ECBCS) - Towards Zero Energy Solar Buildings – will present that there are three key steps to develop a ZEB, providing greater flexibility in the decision making for building design: optimizing the passive building design, maximizing energy efficiency to minimize the building's energy demand, and exploring the generation of onsite renewable energy to cover existing needs (IEA, 2015).

Currently, the technical and economic feasibility of ZEBs is analyzed using parametric simulation (Ferrara *et al.*, 2020). This tool is valuable for the designer, as it allows making low energy suggestions and optimizing the model in the design process at an early stage and in a holistic manner (Lobaccaro *et al.*, 2018).

WHAT IS THE IMPACT OF ZEB TO FACE CLIMATE CHANGE?

Climate change (CC) presents challenges in making adaptation and mitigation measures in buildings. Studies show that it is possible to reduce the sector's emissions by 40% with the technologies available in the market (United Nations Environment Programme – Sustainable Buildings & Climate Initiative, 2009). The mitigation strategies are focused on energy balance, thermal comfort and the interaction with grids (Chai, Huang & Sun, 2019).

The integration of EEC into the built environment, whether through new buildings or the rehabilitation of existing ones, will achieve a greater energy and environmental quality in the constructions, as a response to the need of creating resilient cities that CC brings with it, as this demands more self-sufficient behaviors in the use of resources (Calvente, 2007). It has been shown, in this context, that due to the increase of land temperature, in the future it will be necessary to improve passive solar protection measures and to progress with cooling technologies for the summer period (Flores-Larsen, Filippin & Barea, 2019).

The neutral impact achieved by limiting the consumption of fossil fuels and the neutral energy development during the building's life cycle, can become greater and more positive. The search for the highest efficiency in the administration of non-renewable resources and the maximum generation of those renewable ones, contributes to reaching a superior scale in sustainable building matters (Attia, 2016). In Figure 10, it is seen that the positive development through ZEBs can increase the

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Figure 11. nZEB community, Zero carbon homes, United Kingdom. Source: Photograph taken from the Bioregional Development Group (https://www.bioregional.com/).

biocapacity and reverse the ecological footprint of the building, which can become regenerative buildings.

WHAT ARE THE PROJECTIONS FOR THE IMPLEMENTATION OF ZEBS?

The growth of the ZEB mass has transcended the world in recent years and its continuity is expected. From this point of view, the European Parliament and Council (2018) has declared that

> each member state will set out a long-term strategy to support the renewable of their residential and non-residential building stock, both public and private, transforming them into properties with high energy efficiency and decarbonized before 2050, facilitating the economically profitable transformation of existing buildings into nearly zero energy consumption buildings (European Parliament and Council, 2018, Art. 2 p. L 156/81).

To this, it has to be added that, China recently generated a version of the Technical Regulation for ZEB (*Technical Standard for Nearly Zero Energy Buildings* – GB/T 51350-2019), where it is proposed to reach the objective "three 30% in the future: 30% of new ultra-low energy buildings; 30% of renewable energy for buildings; and 30% of old buildings restored as ultra-low energy buildings" (Luo *et al.*, p. 2, 2020).

In brief, it is expected that the ZEB contribute significantly in smart cities (Kylili & Fokaides, 2015). Facing this challenge, the idea of "nZEB community" is suggested, based on a collaborative concept, where the buildings that belong to them, can freely share RE generation, energy storage and information (Huang & Sun, 2019). Rehman, Reda, Paiho and Hasan (2019) suggest the need of seeking technically efficient and economically affordable energy storage methods. Another example along this line, is the multi-family dwelling program implemented by government policies in the United Kingdom, *Zero Carbon Homes* (Figure 10), which represents a contribution in the transition towards low carbon buildings (Heffernan, Pan, Liang & de Wilde, 2015).

CONCLUSION

In this work, ten questions about ZEB were answered, from a revision of existing literature, with the objective of identifying, developing and understanding their main characteristics.

The state-of-the-art indicates that ZEB are distinguished from other buildings conceived in the framework of sustainability, mainly because of their achievement of a neutral energy balance between energy generation and demand; balance in which it is also possible to consider the amount of CO_2 emissions generated during the building's entire life cycle. This condition can be reached along two lines. The first of these is related better to the holistic parameters of sustainability and is based on energy efficiency, in passive conditioning and, in the restriction of their energy consumption to achieve the neutral balance starting from a very reduced generation of renewable energy. The risk lies in that said neutral balance can also be obtained based on a second line, depending of a great own renewable energy production, that represents an impact itself on climate change. It is proven that, in the RE systems at 100% in autonomous buildings, accumulated GG emissions are generated during the system's entire life cycle; a condition that cannot be solved, reason why it constitutes a great limitation.

Therefore, it is considered essential that, to reach the neutral balance, the greenhouse gas emissions, especially CO_2, are counted throughout the building's entire life cycle.

Energy consumption for heating and cooling tends to be the most compromised in buildings, which is why the literature reviewed proposes achieving savings in the ZEBs of between 25% and 50% respectively, limiting both to 30 kWh/m^2/year.

In some cases, the ZEBs use an energy storage system that tends to be oversized, as the batteries still represent a very inefficient technology, generating a high level of inefficiency and a high investment cost.

In the cases of ZEBs with connection to the grid, the energy generation is aided by the building-grid exchange, so that the user can satisfy their energy needs using RE and return surplus energy to the grid, so that other users can use it. The grid energy remains available only at the times when RE generation is insufficient. Therefore, the possibility of balancing emissions generated by RE during the system's operation is established through an active behavior in energy efficiency matters by the users.

Worldwide, the growth of the ZEB mass has transcended boundaries and it is projected this trend will continue, promoting notions of community and circular economy, which is backed by the support received from regulations of the main developed countries. It is expected that ZEBs, in their path towards high energy efficiency, form part of the paradigm of Regenerative Sustainable Buildings, that seek to contribute to the biocapacity of Earth and to the reduction of the ecological footprint caused by the building sector.

Notwithstanding what has been said, the definitions and diversifications suggested, since their beginnings, in the specialist literature, essentially constitute a theoretical basis over empirical experiences, especially when looking at developing countries. Given that the metric indices can vary depending on their geographical, technological, economical limitations, among others, it can be expected that Latin America generates its own holistic approach adapted to the different conditions and realities that characterize it.

ACKNOWLEDGMENTS

We would like to thank the National Scientific and Technical Research Council (CONICET) for their financial backing to make this research.

APPENDIX

TABLE 1 (PART 1)

EJE TEMÁTICO	UBICACIÓN	AUTOR / AÑO PUBLICACIÓN	FUENTE
DEFINICIONES DIVERSIFICACIONES AUTONOMÍA	PREGUNTA 1	Attia, 2018 Torcellini, Pless y Deru , 2006 Brambilla, Salvalai, Imperadori, & Sesana, 2018 Booth, Barnett, Burman, Hambrick, & Westby, 2010 Congedo, Baglivo, Zacà y D'Agostino, 2015 Good, Andresen y Hestnes, 2015 Harkouss, Fardoun y Biwole, 2019 Moschetti, Brattebø y Sparrevik, 2019 Kilkis, 2007 Hernandez & Kenny, 2010 Comisión Europea, 2010 Piderit, Vivanco, van Moeseke, & Attia, 2019 Delia D'Agostino, 2016 A. Marszal y Heiselberg, 2015 Sartori, Napolitano y Voss, 2012 Mlecnik, 2012	Net Zero Energy Buildings Conference for ACEEE Energy and Buildings NREL Technical Report Data in Brief Solar Energy Energy Energy and Buildings Proceedings of Energy Sustainability Energy and Buildings EU Directive Sustainability Publicaciones de l UE. AALBORG University Energy and Buildings Energy Efficiency
SUSTENTABILIDAD	PREGUNTA 2	Hernández Moreno, 2008 Kristinsson, 2012 Laustsen,2008 Chastas et al., 2018 Attia et al., 2018 Guillén-lambea, Rodríguez-soria, & Marín, 2017 Chastas et al., 2018 Piderit, Vivanco, van Moeseke, & Attia, 2019 Deng et al., 2020 Diana D'Agostino, Marino, Minichiello, & Russo, 2017 A. J. Marszal et al., 2011 Sartori, Napolitano, & Voss, 2012 Moschetti et al., 2019 Seo, Passer, Zelezna, & Hajek, 2016 Fjola et al., 2018 Hernandez & Kenny, 2010a Jusselme, Rey & Andersen, 2018 Moschetti, Brattebø & Sparrevik, 2019 Rodríguez Manrique, Kobiski, & Fassi Casagrande Jr, 2014 Kalbasi, Ruhani, & Rostami, 2019 Wargocki, Zirngibl, Bendžalová, & Mandin, 2020 Petersdorff, Boermans, & Harnisch, 2006 Belausteguigoitia Garaizar, Laurenz Senosiain, & Gómez Telletxea, 2010 De Gisi, Casella, Notarnicola, & Farina, 2016 Javanmard, Ghaderi, & Sangari, 2020	Acta Universitaria Libro Códigos EE Building and Environment Net Zero Energy Buildings Revista Hábitat Sustentable Building and Environment Sustainability Energy Energy Procedia Energy and Buildings Energy and Buildings Energy and Buildings International Energy Agency Energy and Buildings Energy and Buildings Energy Reviews Energy and Buildings, Revista Hábitat Sustentable Journal of Thermal Analysis and Calorimetry Energy and Buildings, EU Directive Sustainable Building Conference Civil Engineering and Environmental Systems Sustainable Cities and Society
TECNOLOGÍAS PASIVAS EFICIENCIA ENERGÉTICA ENERGÍAS RENOVABLES	PREGUNTA 3	Javanmard, Ghaderi, & Sangari, 2020 Li, Yang, & Lam, 2013 Volf et al., 2018 Moga & Bucur, 2018 Bordoloi, Sharma, Nautiyal, & Goel, 2018 Justo Alonso, Liu, Mathisen, Ge, & Simonson, 2015 Liu, Li, Chen, Luo, & Zhang, 2019 Buso, Becchio, & Corgnati, 2017 Hamdy, Nguyen, & Hensen, 2016 Jovanovic, Sun, Stevovic, & Chen, 2017 Osseweijer, Hurk, & Teunissen, 2018 Chen & Norford, 2020	Sustainable Cities and Society Energy Energy and Buildings International Conference Interdisciplinarity in Engineering Renewable and Sustainable Energy Reviews Building and Environment Applied Thermal Engineerin Energy Procedia Energy and Buildings Energy and Buildings Renewable and Sustainable Energy Reviews Energy and Buildings
DEMANDA Y GENERACIÓN DE ENERGÍA	PREGUNTA 4	Berardi, 2018 Kosai & Tan, 2017 U.S.Department of Energy & The National Institute of Building Sciences, 2015 Debbarma, Sudhakar, & Baredar, 2017 Hermelink et al., 2013 Lausten, 2008	Handbook of Energy Efficiency in Buildings Sustainable Cities and Society Reporte organismo Resource-Efficient Technologies European Commission Report International Energy Agency

TABLE 1 (PART 2)

ENERGÍAS LIMPIAS	PREGUNTA 5	Rogelj et al., 2018 Hammond & Jones, 2008 Finnegan, Jones, & Sharples, 2018 Vares, Häkkinen, Ketomäki, Shemeikka, & Jung, 2019 Attia, 2016 Azzouz, Borchers, Moreira, & Mavrogianni, 2017 Hernandez & Kenny, 2010a Lamnatou, Motte, Notton, Chemisana, & Cristofari, 2018	IPCC Inventory of Carbon & Energy Energy and Buildings Journal of Building Engineering Sustainable Cities and Society Energy and Buildings Energy and Buildings Journal of Cleaner Production
IMPACTO EN MATRIZ ENERGÉTICA POLÍTICAS PÚBLICAS	PREGUNTA 6	Lund, Alberg, Connolly, & Vad, 2017 Seljom, Byskov, Tomasgard, Doorman, & Sartori, 2017 DHC, 2012	Energy Energy Euroheat & Power
CONSUMO DE ENERGÍA	PREGUNTA 7	Häkämies et al., 2015 Carpino, Mora, Arcuri, & De Simone, 2017 Causone, Tatti, Pietrobon, Zanghirella, & Pagliano, 2019 Garde et al., 2014 Taleghani, Tenpierik, Kurvers, & Dobbelsteen, 2013 Hermelink et al., 2013 Agostino & Parker, 2020	VTT Technical Research Centre of Finland Building Simulation Energy and Buildings Energy Procedia Renewable and Sustainable Energy Reviews
METODOLOGÍA DE EVALUACIÓN CERTIFICACIÓN	PREGUNTA 8	A. J. Marszal et al., 2011 Comisión Europea, 2010 Delia D'Agostino, 2016 Pacheco-Torgal, 2014 U.S.Department of Energy & The National Institute of Building Sciences, 2015 IEA, 2015	Energy and Buildings DirectivaUE Energy Construction and Building Materials reporte organismo International Energy Agency.
CAMBIO CLIMÁTICO	PREGUNTA 9	UNEP,2009 Chai, Huang, & Sun, 2019 Calvente M., 2007 Flores-Larsen, Filippín, & Barea, 2019 Attia, 2016	Reporte organismo Energy Resiliencia : un concepto clave para la sustentabilidad Energy and Buildings Sustainable Cities and Society
PROYECCIONES FUTURAS COMUNIDAD ZEB	PREGUNTA 10	Parlamento Europeo y del Consejo, 2018 Luo et al., 2020 Kylili & Fokaides, 2015 Huang & Sun, 2019 Rehman, Reda, Paiho, & Hasan, 2019 Heffernan, Pan, Liang, & de Wilde, 2015	DirectivaUE Applied Energy Sustainable Cities and Society Applied Energy Energy Conversion and Management Energy Policy

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https://doi.org/10.22320/07190700.2020.10.02.03

Recibido 25/08/2020
Aceptado 05/12/2020

INFLUENCE ON ENERGY PERFORMANCE IN HISTORICAL BUILDINGS CAUSED BY THE URBAN ENVIRONMENT AND PROJECT MODIFICATIONS: THE CASE OF THE DUCLÓS HOUSE

INFLUENCIA EN EL RENDIMIENTO ENERGÉTICO EN EDIFICIOS HISTÓRICOS PROVOCADO POR EL ENTORNO URBANO Y LAS MODIFICACIONES DE PROYECTO: EL CASO DE LA CASA DUCLÓS

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RESUMEN

Los edificios históricos constituyen parte fundamental del patrimonio cultural tangible de la sociedad actual. El cumplimiento de las exigencias de ahorro energético para mitigar el cambio climático, sin embargo, puede verse limitado aquí debido a las características propias de estos edificios. Además, en el caso de las construcciones históricas, los principios de diseño bioclimático aplicados por los arquitectos, desde principios del siglo XX hasta la actualidad, pueden haber perdido efectividad. Ello ocurre, a veces, por las modificaciones en proyecto o por efectos del desarrollo urbanístico. En este estudio se analizan estos dos aspectos en un determinado edificio histórico ubicado en Sevilla: la Casa Duclós de José Luis Sert. Este presenta modificaciones en la cubierta, cuando se compara la proyectada y la construida. Asimismo, su entorno urbano se ha transformado desde que la Casa fue edificada. Para el análisis expuesto en este artículo, se realizaron simulaciones energéticas utilizando datos climáticos correspondientes al periodo 2000-2019. Los resultados muestran la influencia que tuvieron las modificaciones de la cubierta proyectada y la expansión urbanística en el rendimiento energético del edificio, con respecto a la concepción original del inmueble.

Palabras clave
patrimonio arquitectónico, ahorro de energía, estrategias urbanas, arquitectura moderna.

ABSTRACT

Historic buildings are a fundamental part of the tangible cultural heritage of today's society. However, the energy saving requirements to limit climate change may present limitations with respect to the characteristics of these buildings. In the case of historical buildings from the early 20th century to the present, the bioclimatic design principles applied by architects may have been limited. In some cases, it may be due to project modifications or urban expansion. In this study, these two aspects are analyzed in a case of a historic building located in Seville: The Duclós House by José Luis Sert. This building presents modifications in the roof between the projected and the built one. Likewise, the urban environment is different from the one existing when it was built. The analysis was carried out with energy simulations using weather data from 2000 to 2019. The results show the influence that the modifications of the projected roof and the urban expansion had on the energy performance of the building with respect to the original idea of the building.

Keywords
Architectural heritage, energy saving, urban strategies, modern architecture

Revista Hábitat Sustentable Vol. 10, N°. 2. ISSN 0719 - 0700 / Págs. 42 -53
https://doi.org/10.22320/07190700.2020.10.02.03

INTRODUCTION

Currently, there is a clear goal of attaining energy savings in existing buildings (Akande, Odeleye, Coday & Jimenez Bescos, 2016). Although most studies have focused on the energy analysis of residential, administrative or commercial buildings, a lack of research dedicated to analyzing the energy performance of heritage buildings has been detected (Lidelöw, Örn, Luciani & Rizzo, 2019). The ones there are have focused on reducing energy consumption to guarantee suitable conditions of conservation (De Rubeis, Nardi, Muttillo & Paoletti, 2019) or the suitable inhabitability for their users (Sugár, Talamon, Horkai & Kita, 2020). However, despite these efforts, there is a lack of studies considering the impact modifications of heritage buildings have had on their energy performance. Aspects like urban expansion, can modify the energy performance of buildings, on altering their shading conditions (Lobaccaro et al., 2019). An example of this was reported by Baño Nieva and Vigil-Escalera del Pozo (2005) for a building with greenhouses that favor solar radiation capture in Madrid. Urban growth led to higher buildings appearing around it, meaning the architects' previous design will be unused. Factors like the imposition of regional traditional techniques in the construction processes for these buildings are added to this, which can lead to changes in energy performance compared to what was originally projected.

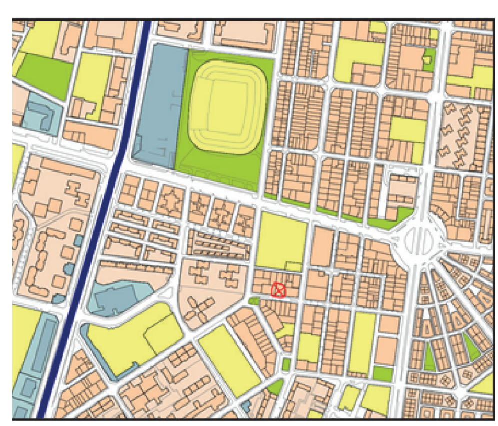
Facing these circumstances, this study sets out to analyze the current energy impact of a historic building from the start of the 20th century, considering the modifications it has undergone, both from building work and urban growth. The case chosen was Duclós House built in 1930, a project by José Luis Sert, and located in Seville (Spain). José Luis Sert was one of the most important Spanish architects in the last century. Despite its importance, the work of Sert in Spain is limited. From his few Spanish constructions, Duclós House constitutes, without a doubt, the his most forgotten work on an international scale, which is why there is limited research on it (López-Rivera & Parra Bañón, 2012). Just like other famous buildings of the period, like those of Frank Lloyd Wright (Beltrán-Fernández, García-Muñoz & Dufrasnes, 2017) or Le Corbusier (Iommi, 2019), Sert's work is characterized on having a major bioclimatic component in his projects.

Concretely, there is certainty that modifications were made on the house compared to its specifications. This is likely because of a lack of direction during the works:

> In this regard, the information we have is unclear. Sert tells us that he visited the site and works on several occasions, but he does not remember the precise details about the direction […]. The owners tell us about certain modifications made during the construction […] (Delgado Pérez, Pérez Escolano, Sebastián Bollaín & Ramón Sierra, 1968, p. 177).

The building was located in an area far from the urban hub when it was built: a smallholding marked out by the architect Aníbal González on lands of the University Chancellor's farmhouse, which later became popularly known as the Nervión neighborhood (Bono Ruiz de la Herrán, García Vásquez, Pérez Escolano, Pico Valimaña & Ortega, 1996). It was an unconsolidated suburban development area, even a decade after its construction, just as can be seen in Figure 1. However, urban expansion throughout the 20th century enveloped Duclós House, leaving it located on a narrow street, surrounded by high-rise buildings (Figure 1).

1945



Today

Figure 1. Plans of the area around Duclós House in 1945 (left) and today (right). Source: Preparation by the authors using plans from the map library and the Seville City Council's General Urbanistic Ordinance Plan.

As a result, the case study chosen meets the expected conditioning aspects to be analyzed. First of all, a review of the construction details is made which has differences between what was built and what was projected: the roof. After this, an energy analysis was made of the impact of the modifications made has implied, both on the roof and on the urbanistic surroundings of the building, using climate data from the last 20 years in Seville.

CONSTRUCTIVE ANALYSIS OF DUCLÓS HOUSE

Duclós House is located in Seville. It is a single-family dwelling located on a 535 m² smallholding (Figure 2) that occupies a surface area of 169 m². The house's vertical distribution comprises the following floors: semi-basement, ground floor, second floor and attic. Connection between the different levels is made through single flights of stairs (Quesada, 2008).

The ground floor has a hall, kitchen, garage, laundry and large L-shaped living room, whose initial layout formed a sitting room and the old living room. The second floor is split into four bedrooms, two bathrooms and two terraces. After a reorganization, the floor's distribution was left with 3 bedrooms, two bathrooms, a sitting room and two terraces (Lousame, 2011). The attic has a laundry room, which was closed off to leave space to hang clothes protected from the rain. It has also a box room, a bedroom, a bathroom and a terrace (Lousame, 2011).

CONSTRUCTION DESCRIPTION

The house's foundation is built from a 50 cm thick concrete slab, on which the finishing material of the basement floor was placed. The walls of this floor are 50 cm thick concrete, without any type of insulation or drainage, and the framework is made from 25 cm thick reinforced concrete (Bono Ruiz de la Herrán et al., 1996).

As for the enclosures, Sert designed the dwelling bearing in mind its bioclimatic interaction with its surroundings. For this reason, the building has two different façade setups, depending on their orientation. The north-facing façade comprises a traditional 25 cm solid wall, while the rest of the façades are built by two rows of bricks separated by an unventilated air chamber (Lousame, 2011). The building's carpentry is spread along all its façades, with different rectangular shapes. One of the aspects that most affects passive comfort strategies is the handling of the openings. At Duclós House, there are openings on most of the façades, but more so on the north-facing one. The rest of the openings have

Figure 2. Outdoor photograph of Duclós House.Source: Quesada (2008, p. 194).

Figure 3. Aerial view of Duclós House and the buildings around it. Source: Preparation by the Authors.

shading elements like the windows set back from the wall on the ground floor of the south façade. With these systems, direct solar incidence in summer periods can be avoided, when it is high in the sky, as well as direct incidence in winter, when the sun is lower.

As has been indicated, the building is currently surrounded by large voluminous high-rise buildings (Figure 3), that limit the incidence of direct solar radiation on each of its enclosure elements, as such the different shading premises considered in the project's preparation may have been left inoperative, impeding, in winter, the solar incidence that can generate greater thermal comfort in the different rooms.

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ROOF

The roof is one of the most significant elements of Duclós House, on being the element that is most exposed to solar radiation. It was projected following the constructive typology of the Catalan roof, but the lack of site direction by the architect led to the roof being built following the construction techniques of the region at that time (Paricio Casademunt, 1998). In spite of this, the roof has a relevant solar radiation most of the year. Sert understood that the terrace was a further extension of the house and, for that reason, wanted to implement three clearly identified strategies for the protection and search of indoor comfort: the creation of a high-rise garden, the positioning of a manual awning using a metal support, and a ventilated roof. Ultimately, on facing diverse casuistries, an Andalusian roof was chosen (Lousame, 2011)

On analyzing the project's graphical documentation, the space set aside for an air chamber can be seen, on the building's floor plan (Figure 4), which corresponds to the project's original idea; although there is evidence, like the lack of vents or the 13x28 cm ceramic tiles, that indicate the terrace roof was built following the canyons of traditional Andalusian roofs (Lousame, 2011).

In this way, there are signs that show that the roof was projected with an air chamber. However, the fact that Duclós House lacks vents is one of the reasons why it is assumed that the projected roof could not be made (Paricio Casademunt, 1998). In this sense, it is worth mentioning another project of José Luis Sert which was designed at practically the same time as Duclós House: the building on Muntaner Street, in Barcelona (Spain). This building has a particular solution using the traditional Catalan roof of the time. By analyzing the graphical documentation of said project, the same type of representation seen on the plans of Duclós House can be seen (Figure 5). According to several research projects, the solution set out by Sert would use a mixed proposal of a traditional Catalan roof on honeycomb walls and the solution used by Le Corbusier and Jeanneret at the Double House in Weissenhofsiedlung, with the flooring placed on sand and filtering gravel, under which it had a waterproofed layer (Lousame, 2011; Paricio Casademunt, 1996).

The traditional Catalan roof of the time was formed by two wrought panels: one horizontal and the other with a slope of between 6% and 8%, supported on wooden or metal profile joists. But, since the beginning of the 20th century, it became a model formed by a floor tile board underpinned on honeycomb walls. The air ventilation in both cases would be produced by the façade and the indoor

Figure 4. Duclós House floor plan. Source: Preparation by the Authors.

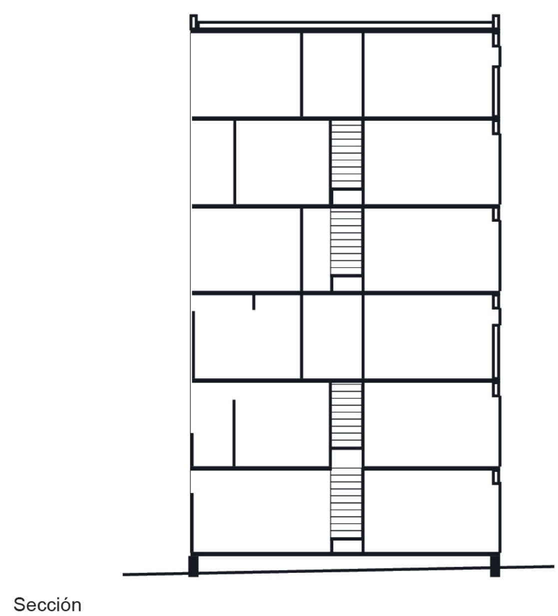

Figure 5. Floor plans of the building on Muntaner Street. Source: Preparation by the Authors.

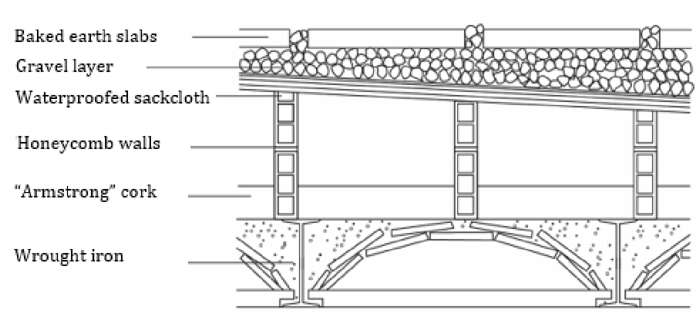

Figure 6. Floor plans of the building on Muntaner Street.Source: Paricio Casademunt (1996, p. 421).

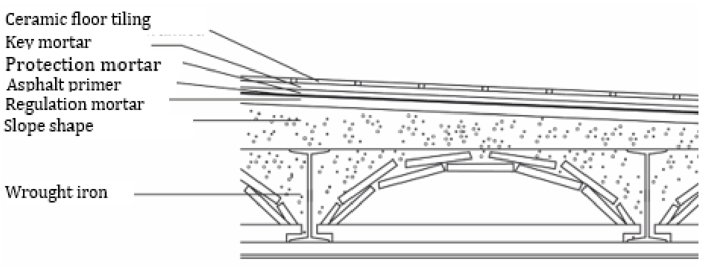

Figure 7. Construction detail of the roof implemented at Duclós House. Source: Preparation by the Authors.

patios, creating air circulation that dries up any leaks produced by the deck.

Therefore, although the type of roof projected for Duclós House is unknown, due to the complete lack of literature, the construction details of the roof on Muntaner Street are known accurately (Figure 6). It is made from a floor tile laid on honeycomb walls, on which a waterproofed sackcloth was laid, a layer of regularization gravel that acted as a drainage layer and a finish using 43 x 43 cm slabs, with a 2.5 cm joint between pieces. Inside the ventilated chamber, between the honeycomb walls, compressed cork from the Armstrong Cork Company was used as insulating material (Olona, 2015; Paricio Casademunt, 1996).

Now, the roof actually made was not the one projected. It is worth clarifying that there are not data about the construction details of the roof implemented. Facing the impossibility of determining its composition through any other type of tests, destructive or non-destructive, an estimation of is composition was made through the analogy with other similar constructions of the time (Ficco, Iannetta, Ianniello, D'Ambrosio Alfano & Dell'Isola, 2015). In this way, it is agreed that the type of roof constructed is built by a lightened concrete slope shape with a variable thickness, on which a mortar regulation layer was applied for the later asphaltic primer. Over said primer, at the same time, a layer of protection mortar was applied and the ceramic finish were placed with their corresponding key mortar. As a result, it can be stated that the roof does not have any element with a low thermal conductivity that can be used as insulation.

METHODOLOGY

The methodological flow of the research consisted in an energy simulation process performed using DesignBuilder, the main steps of which

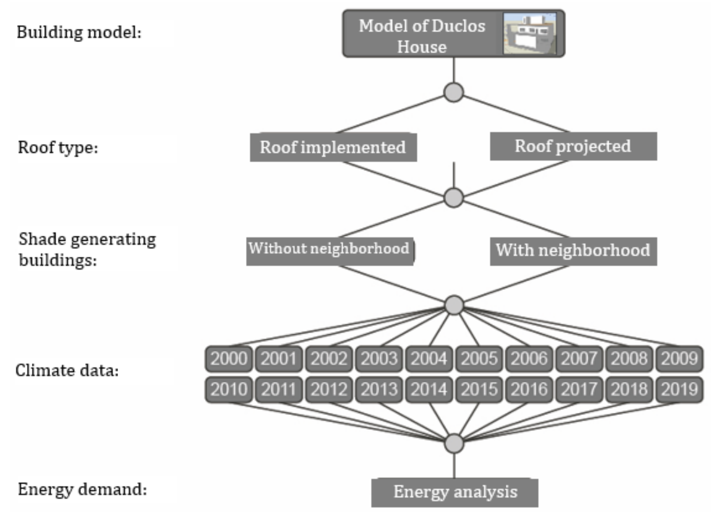

Figure 8. Work flow followed in the research. Source: Preparation by the Authors.

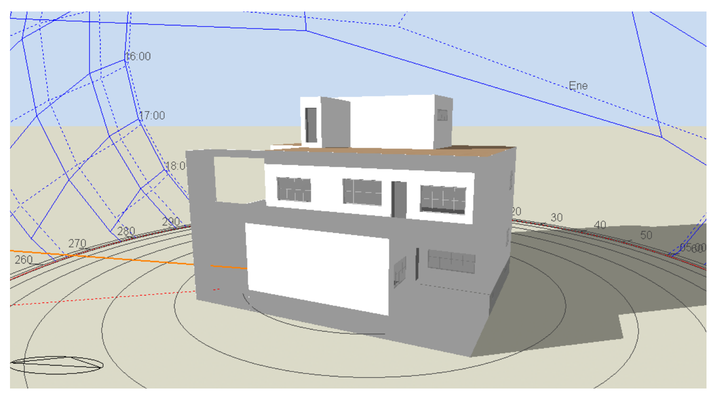

Figure 9. Model of Duclós House in DesignBuilder. Source: Preparation by the Authors.

are summarized in Figure 8. Just as can be seen, Duclós House was modeled first (Figure 9). For this, the available planimetric data of the project was used and the enclosures were defined using the construction details described in the previous sections. Table 1 indicates the thermal conductivity values and the thicknesses of the layers of the main elements of the envelope. The thermal conductivity values used are those established in the Construction Elements Catalog and in the energy certifications tools in Spain. It is worth highlighting that two models were defined considering the roof type: projected roof (with chamber) and implemented roof (flat Andalusian). In Table 2, the thermophysical properties set out for each roof are detailed.

Likewise, two types of models were designed to value the presence or absence of surrounding buildings. The lack of buildings would allow analyzing

Element	Layer	Thickness (m)	Thermal conductivity (W/(mK))
Facade	Cement mortar	0.020	1.80
	Brick wall	0.10	0.43
	Cement mortar	0.020	1.80
	Air chamber	0.05	0.025
	Hollow brick wall	0.05	0.313
	Gypsum plaster	0.015	0.57
Basement wall	Mass concrete	0.50	1.65
Basement floor	Mass concrete	0.15	1.65
	Cement mortar	0.02	1.80
	Clay floor tile	0.10	2.30

Table 1. Layers, thicknesses and thermal conductivity of the façade and the basement floor and walls considered in the energy simulation process. Source: Preparation by the Authors.

Element	Layer	Thickness (m)	Thermal conductivity (W/(mK))
Roof implemented	Finish	0.010	1.00
	Key mortar	0.01	1.80
	Protection mortar	0.015	1.80
	Asphalt primer	0.004	0.23
	Regulation mortar	0.015	1.80
	Lightened concrete	0.20	1.15
	Slab	0.25	2.5
	Gypsum plaster	0.015	0.57
Projected roof	Finish	0.010	1.00
	Layer of gravel	0.050	1.00
	Waterproofing sackcloth	0.013	0.23
	Ceramic floor tiling	0.04	0.29
	Air chamber	0.02	-
	Compressed cork	0.04	0.10
	Slab	0.25	2.5
	Gypsum plaster	0.015	0.57

Table 2. Layers, thicknesses and thermal conductivity of the roofs implemented and projected. Source: Preparation by the Authors.

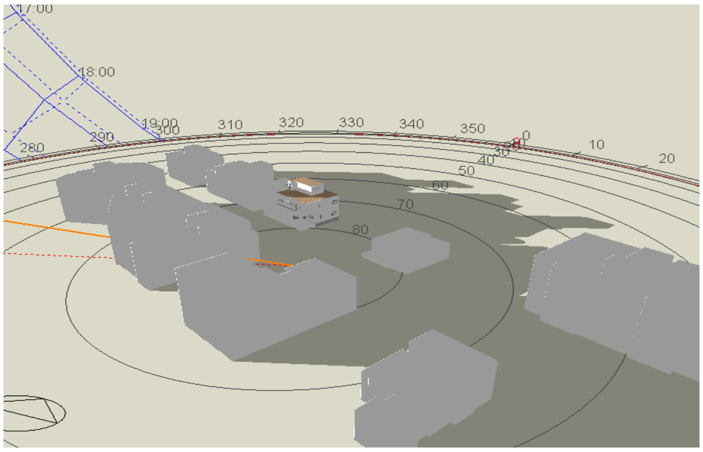

Figure 10. Model of Duclós House with the surrounding buildings in DesignBuilder.Source: Preparation by the authors.

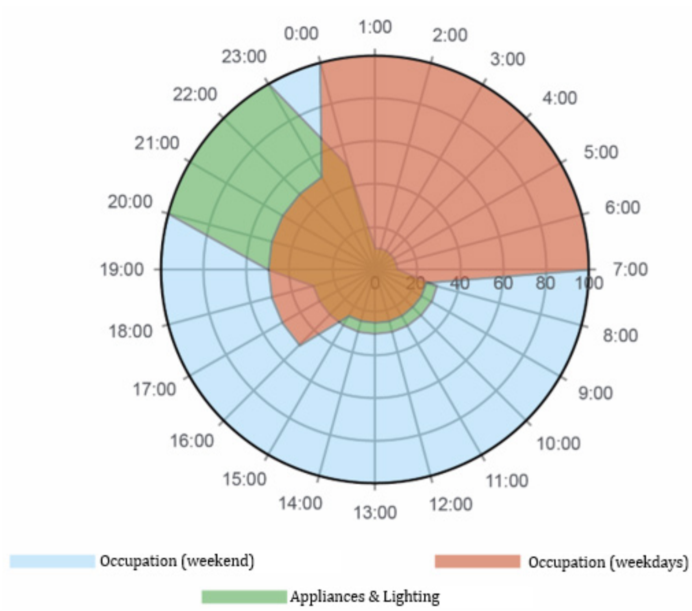

Figure 11. Percentage distribution of the residential profile loads of the Technical Building Code. Source: Preparation by the Authors.

the energy performance of the building if large buildings had not been built around it, while analysis with the surrounding buildings allows valuing the current energy performance. With this purpose, the cartographic database was downloaded to model the neighboring buildings, considering a height of 3 meters per floor (Figure 10).

Regarding the operational patterns of air-conditioning systems and load profiles, the profile defined for residential buildings in the Technical Building Code was used. This considers three load types (occupation, equipment and lighting) and establishes two different distribution types depending on the type of day (working day and

System	Months	Setpoint temperature/period of the day			
		0:00-6:59	7:00-14:59	15:00-22:59	23:00-23:59
Heating System	October – May	17	20	20	17
Air-conditioning system	June - Sept	27	-	25	27

Table 3. Hourly values of the setpoint temperatures defined in the residential profile of the Technical Building Code. Source: Preparation by the Authors.

weekend). In Figure 11, the percentage load distributions of said profile are shown. The maximum load value of the equipment and lighting systems is 4.4 W/m^2; while, for occupation, a maximum value is established for the sensitive load and for the latent load of 2.15 W/m^2 and 1.36 W/m^2, respectively. As for the operational pattern of the air-conditioning systems, the Technical Building Code distinguishes two periods of operation considering the time of the year. In Table 3, the temperature setpoint values and hours considered in said residential profile are indicated. It is important to clarify that by including, in the comparisons, the status of the buildings without the neighborhood does not cover the objective of determining the energy performance in 1930, as at that time there were no active systems for these purposes; what is intended is to evaluate the consequences urban expansion has had on the building's energy performance, considering the demands of users in the 21st century.

As for the climate data, the hourly temperature and relative humidity values were compiled from 2000 to 2019 in Seville, using the Spanish State Meteorology Agency's data. With these hourly data, specific EnergyPlus Weather files were designed for each year, so that energy simulations could be made that would simulate the energy performance of the case study every year. It is worth mentioning that the years prior to 2000 were not simulated because of the lack of hourly data in Seville. Finally, given that the case study was analyzed combining the roofs and urban surroundings with climate data of the last 20 years, the results of this analysis are based on a simulation process comprising a total of 80 simulations.

RESULTS AND DISCUSSION

The analysis of the results was based on the modifications detected in the building's annual energy demand. These data are expressed, first of all, in Figure 12, where the

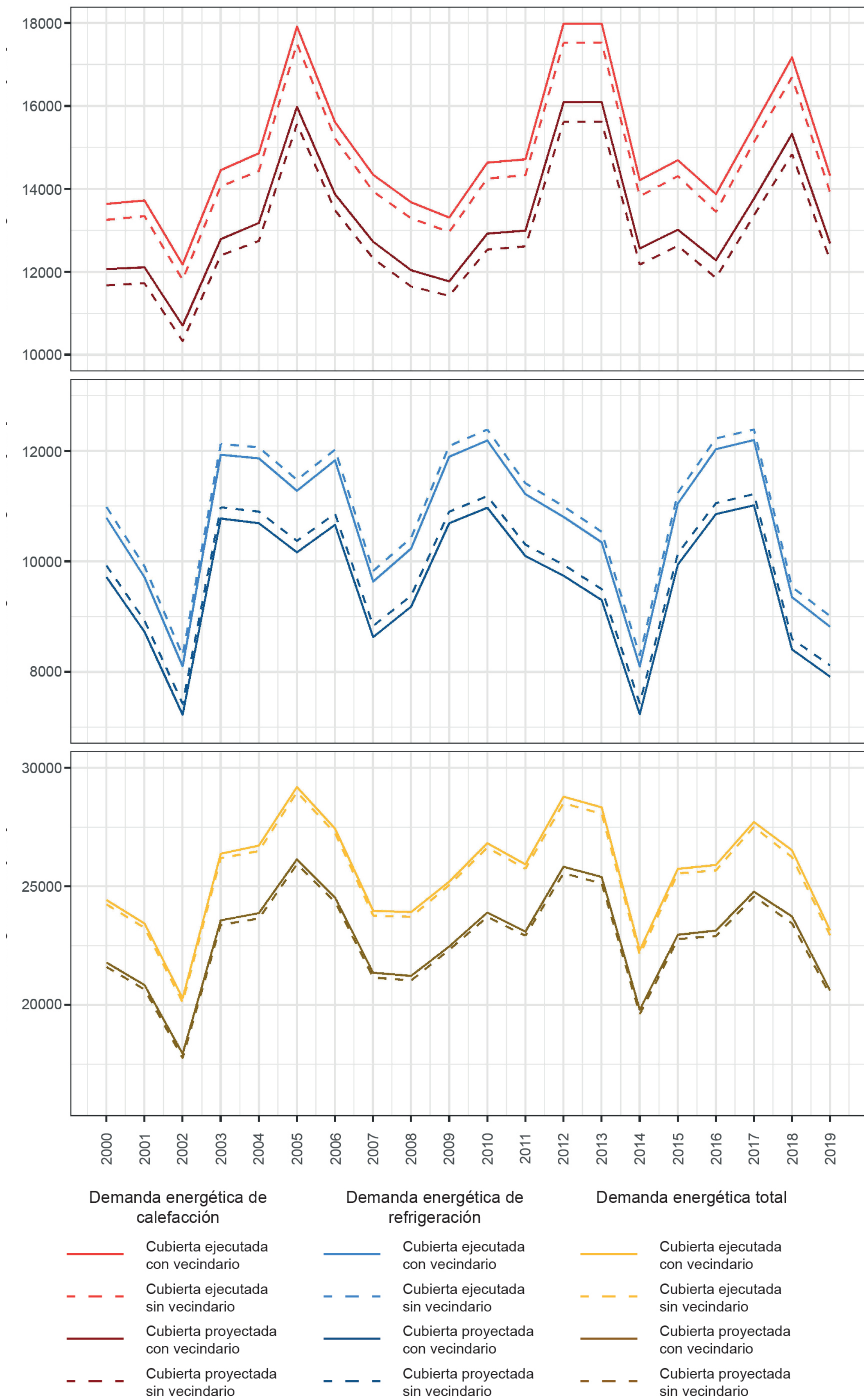

Figure 12. Annual energy demand values obtained with the different assumptions considered. Source: Own Preparation

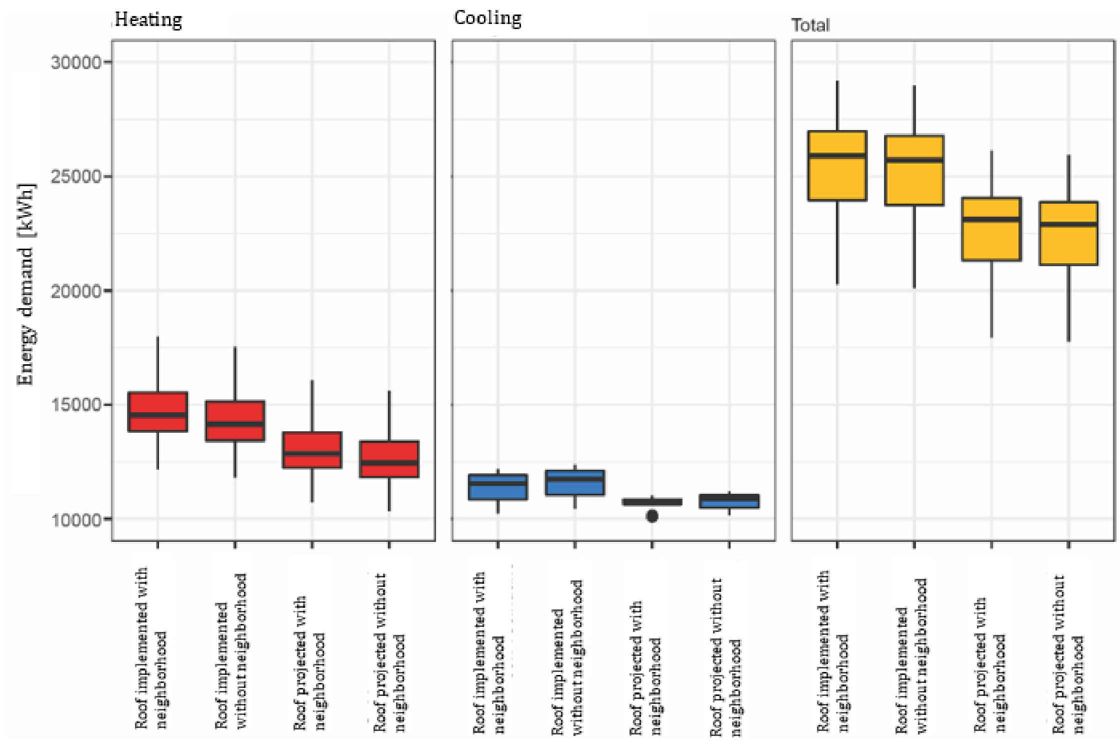

Figure 13. Box plot of the annual energy demand distributions of each assumption considered for Duclós House. Source: Preparation by the Authors.

time series obtained of the energy demands with the different assumptions of Duclós House are included. Just as can be seen, the roof style projected by Sert constitutes a roof typology with a lower energy demand. However, the urbanistic expansion phenomenon has altered the case study's energy performance, although this modification depends on the type of energy demand: with respect to the heating energy demand, the projected case study, without a neighborhood, had lower values; while, the cooling energy demand, had higher values. Despite this, the higher percentage contribution of the heating energy demand in the total energy demand (as it obtained higher values than the cooling energy demand throughout the year) means that the most suitable combination is the projected house without a neighborhood.

To see this aspect in greater detail and in a quantified way, the values of quartiles obtained in the annual energy demand distribution of recent years (i.e., 2000-2019), are presented in Figure 13. In this way, the case with neighborhood is the one that has the highest quartile values in the heating energy demand. Concretely, there is a higher value here of between 386.5 and 412.38 kWh compared to the current case without neighborhood, and of between 1,597.93 and 2,149.35 kWh in the different assumptions of the projected case study. This same trend is detected in the total energy demand, with values over 204.62 kWh compared to the building implemented without neighborhood and of up to 3,104.14 kWh in comparison with the building projected by Sert. This means significant percentage deviations (Figure 14) and proves the worse energy performance that Duclós House currently has.

Figure 14 shows the average saving obtained between the different assumptions of Duclós House compared to the existing case. In this way, it can be seen that the changes in the design and the surroundings have led to a worse energy performance. In this sense, although the urbanistic growth has implied an improvement in the cooling energy demand (with an average saving of 193.70 kWh), the effect on the total energy demand is negative (with an average increase of 207.68 kWh in the energy demand). However, where the highest difference is detected is between the type roof typologies analyzed: the roof projected by Sert implies significant average savings in all energy demands (of 2,762.91 kWH in the case with neighborhood and of 2,966 kWh without it). As was to be expected, the surrounding buildings have a different saving effect in terms of the energy demand, but, due to the operational criteria established by the Technical Building Code, this generates a better performance, when this is a setting without buildings. In any case, this performance could change in the coming years, on facing a progressive increase of the outdoor temperature as a result of climate change.

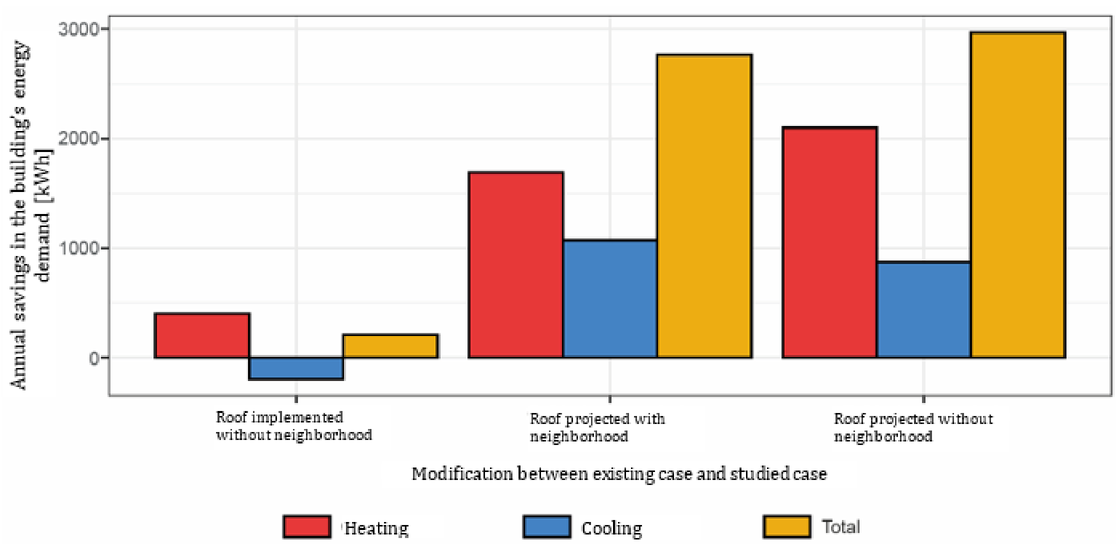

Figure 14. Average saving in energy demand between the current status of Duclós House (executed roof and surrounding buildings) and the other models considered. Source: Preparation by the Authors.

CONCLUSION

The results of this study reveal the great effect that urbanistic growth can have on the energy performance of heritage buildings. The results show how the bioclimatic strategies designed by Sert for openings are nullified with the bigger surrounding buildings. It is a good idea to analyze this aspect, which a priori could be negative, in a longer temporal context, as it could be foreseeable that, through the 21st century when considering climate change, this greater shading is beneficial for users of the house. In any case, it is essential to examine existing surrounding elements and their status at the time of its construction to know in detail the energy transformations the building has experienced throughout its history. This factor could explain the possible measures adopted by users of the dwelling throughout its history. For example, in the case of Duclós House, the reasons that led its residents to not place the awning projected by Sert are unknown, although one possibility, in this sense, is that greater shading was achieved with the surrounding buildings.

Likewise, the importance that the detailed study of the constructive and projected characteristics of heritage buildings may have to establish energy savings measures is proven. Specifically, in this research, the analysis of graphical documentation and later energy analysis reflected that the characteristics projected for Duclós House present a better energy performance than those which were finally implemented following traditional local construction techniques. This can be used as a starting point to design improvement measures in this type of buildings. In addition, the repercussions of urban growth on historic buildings have been shown. Although it is obvious that the design patterns of historic buildings did not seek energy efficiency, it is also true that the architects and designers could seek suitable thermal comfort conditions. By using sunlight techniques through the openings, they could effectively have sought to increase thermal loads in cold periods and improve thermal conditions indoors. Despite this, it has been shown that urban growth, without considering the integration of existing historic buildings, may affect their energy performance. Summarizing, the results of this work show the affectations that, at an energy level, urbanistic growth may represent for this type of buildings, as well as the need to make this type of assessment on facing the possible limitations in retrofitting that these properties have, on being protected by public institutions.

To finalize, it must be added that, beyond the results of this research, analysis of the energy performance of these buildings to face the climate evolution expected throughout the 21st century is left outstanding. Performing studies with climate data designed following the climate change scenarios foreseen by the Intergovernmental Group of Experts on Climate Change, would allow more suitably establishing the energy savings measures needed to reach the category of almost zero energy consumption buildings in these constructions.

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Revista Hábitat Sustentable Vol. 10, N°. 2. ISSN 0719 - 0700 / Págs. 54 -69
https://doi.org/10.22320/07190700.2020.10.02.04

Recibido 19/05/2020
Aceptado 02/11/2020

ASSESSMENT OF EARTH BLOCKS BY MEANS OF A CONSTRUCTION FEASIBILITY STUDY (CFS)

EVALUACIÓN DEL BLOQUE DE TIERRA MEDIANTE UN ESTUDIO DE VIABILIDAD CONSTRUCTIVA (EVC)

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RESUMEN

Aunque la construcción con bloques de tierra (BT) está avalada por numerosos trabajos científicos, existe una desconfianza sobre su viabilidad constructiva, agravada por la falta de formación técnica específica. Ante esta incertidumbre, muy presente en el ámbito español, es preciso dar respuestas técnicas fundamentadas. En esa dirección, este artículo expone el diseño y validación de una herramienta para la evaluación de la viabilidad constructiva del BT. Con ese fin, se seleccionan 29 casos de estudio en España, con los que se establecen las determinaciones constructivas y los indicadores para la evaluación de un grado de idoneidad técnica. Este parámetro, como resultado de la herramienta propuesta, sirve como apoyo a la toma de decisiones, la mejora del diseño y la eficiencia de las soluciones que emplean BT. Se concluye con la validación de la herramienta que demuestra su fiabilidad y adaptabilidad a cualquier situación. Finalmente, a partir del análisis de casos, se expone cómo la calidad del producto unida a condiciones externas adversas, aún con diseños constructivos correctos, define una situación común por la que el grado de idoneidad de la solución es reducida. Por lo tanto, es necesario exigir también productos con avales y prescripciones que garanticen y ofrezcan suficiente seguridad técnica.

Palabras clave

construcción sostenible, materiales tradicionales, bioconstrucción, cerramiento de la edificación

ABSTRACT

Although earth block construction (EB) is supported by numerous scientific works, there is a lack of confidence in its constructive viability, aggravated by the lack of specific technical training. In view of this uncertainty, which is widespread in Spain, it is necessary to provide well-founded technical responses. This article, considering these aspects, presents the design and validation of a tool to assess the constructive viability of EB. For this purpose, 29 case studies are chosen in Spain, which establish the constructive use determinations and indicators to assess a degree of technical suitability. This parameter, as a result of the proposed tool, acts as a support for decision-making, the improvement of the design and, the efficiency of the solutions that use EB. It concludes by validating the tool, demonstrating its reliability and adaptability to any situation. Finally, the case analysis shows how the quality of the product combined with adverse external conditions, even with correct construction designs, defines a common situation where the degree of suitability of the solution is reduced. Therefore, it is also necessary to demand products with guarantees and prescriptions that ensure and offer sufficient technical safety.

Keywords

Sustainable construction, traditional materials, bio-construction, building envelope.

Revista Hábitat Sustentable Vol. 10, N°. 2. ISSN 0719 - 0700 / Págs. 54 -69
https://doi.org/10.22320/07190700.2020.10.02.04

NOMENCLATURE

CFS	Construction feasibility study
EB	Earth block
CEB	Compressed earth block
EEB	Extruded earth block
C-CA	Reference to the quality of the product
C-RC	Reference to the construction requirements
C-AE	Reference to the external actions
CFS	Construction feasibility study
GI_i	Degree of suitability for *i* aspects
NET_q	Technical assessment level of the *q* indicators
$NETP_i$	Weighted technical assessment level for *i* aspects
W_i	Weighted coefficient for the *i* aspects

INTRODUCTION

Over the last two decades, the international environmental and economic situation is generating the need and interest to develop suitable construction solutions for the environmental, energy and social demands. In this context, the use of adobe and earth blocks (EB), that mainly includes compressed earth blocks (CEB), as manufactured masonry, may be a more sustainable construction alternative.

To support this statement, the current EB research framework has focused on studies about their mechanical (Gandia, Gomes, Corrêa, Rodrigues & Mendes, 2019; Mahmood, Habeeb & Al-Jumaili, 2019), thermal (Mosquera, Canas, Cid-Falceto & Marcos, 2014; Molar-Orozco, Velázquez-Lozano & Vázquez-Jimánez, 2020; Miloudi *et al*, 2019; Wati, Bidoung, Damfeu, & Meukam, 2020) and durability (Fernandes, Peixoto, Mateus & Gervásio, 2019; Lavie Arsène, Frédéric & Nathalie, 2020; Jové Sandoval, Muñoz de la Calle & Pahíno Rodríguez, 2011) properties. Others support the use of EB, arguing economic aspects, low toxicity and, even, as a product that benefits indoor air quality (Fernandes et al., 2019). It also uses natural local materials, freeing, to a great extent, the environmental impact associated to transportation (Deboucha & Hashim, 2011).

From the application point of view of the product, it is necessary that EB reaches a higher level of acceptance, similar to that of other construction materials, and that certain factors that negatively affect the decision-making of technicians are overcome: the production cost, the low availability of technical data of the product to justify regulatory requirements, added to the bad practice on not knowing the application conditions of the material. As a result, it is necessary to establish a framework that better defines the construction, economic or environmental determinations of using EB. These must serve as the basis for its choice to be viable and guaranteed with technical data and for the trusts of all the agents involved in the construction grows, with the purpose of setting directives on the correct use, and in line with the technical-construction requirements.

The feasibility of using CEB and adobe has been analyzed by Maldonado Ramos, Castilla Pascual, Vela Cossio and Rivera Gómez (2001) demonstrating that, for a small to mid-sized scale project, it is an economic solution, as well as being an improvement for thermal insulation compared to other materials like concrete, bricks or steel. Likewise, in the international regulatory sphere, there are several documents that regulate the use and application of EB, such as the Brazilian (1986-1996), Colombian (2004), Peruvian (2000) or Spanish (2008) regulations, all of them reviewed and analyzed by Cid-Falceto, Mazarrón and Cañas (2011). However, none of the contributions mentioned offer a tool that allows analyzing the feasibility of applying EB in buildings, reason why its applicability is reduced on being subjected to a technical criterion without enough or suitable knowledge regarding its qualities and performance.

As for the assessment methodologies, those that use quantitative or qualitative indicators have been extensively developed in literature. In terms of those focused on earth construction, the contribution of Canivell for the evaluation of adobe brick factories stands out (Canivell, Rodríguez-García, González-Serrano & Romero Girón, 2020; López-Zambrano, Canivell & Calama, 2019). Although its purpose is focused on the evaluation of the physical risk, certain operating capacity of the indicators have been taken as reference. However, no methodological tools that are useful to evaluate the suitability of certain construction products like EB, have been developed.

This work focuses on the construction aspects that affect the suitability of EB as a product, for which its physical, chemical and mechanical characteristics have been defined, as have the production phases and construction techniques for the sake of adopting solutions adapted to different contexts. In this case, the framework of the requirements to analyze the feasibility of EB is the Spanish building regulation (Spain, 2008). The goals of this article are (I) establishing the construction determinations of EB and its associated indicators; (II) presenting and validating the methodological procedure of a tool to evaluate the construction aspects of an architectonic design at the level of basic project developed using EB; (III) presenting the results of said tool in the case studies considered; and (IV) analyzing the response of the indicators used. It is estimated that this task, namely, clearly establishing the demands and determinations of this tool, offering an analysis of the indicators, will facilitate decision-making in this aspect and, subsequently, will contribute towards optimizing the applicability of EB as a sustainable construction solution.

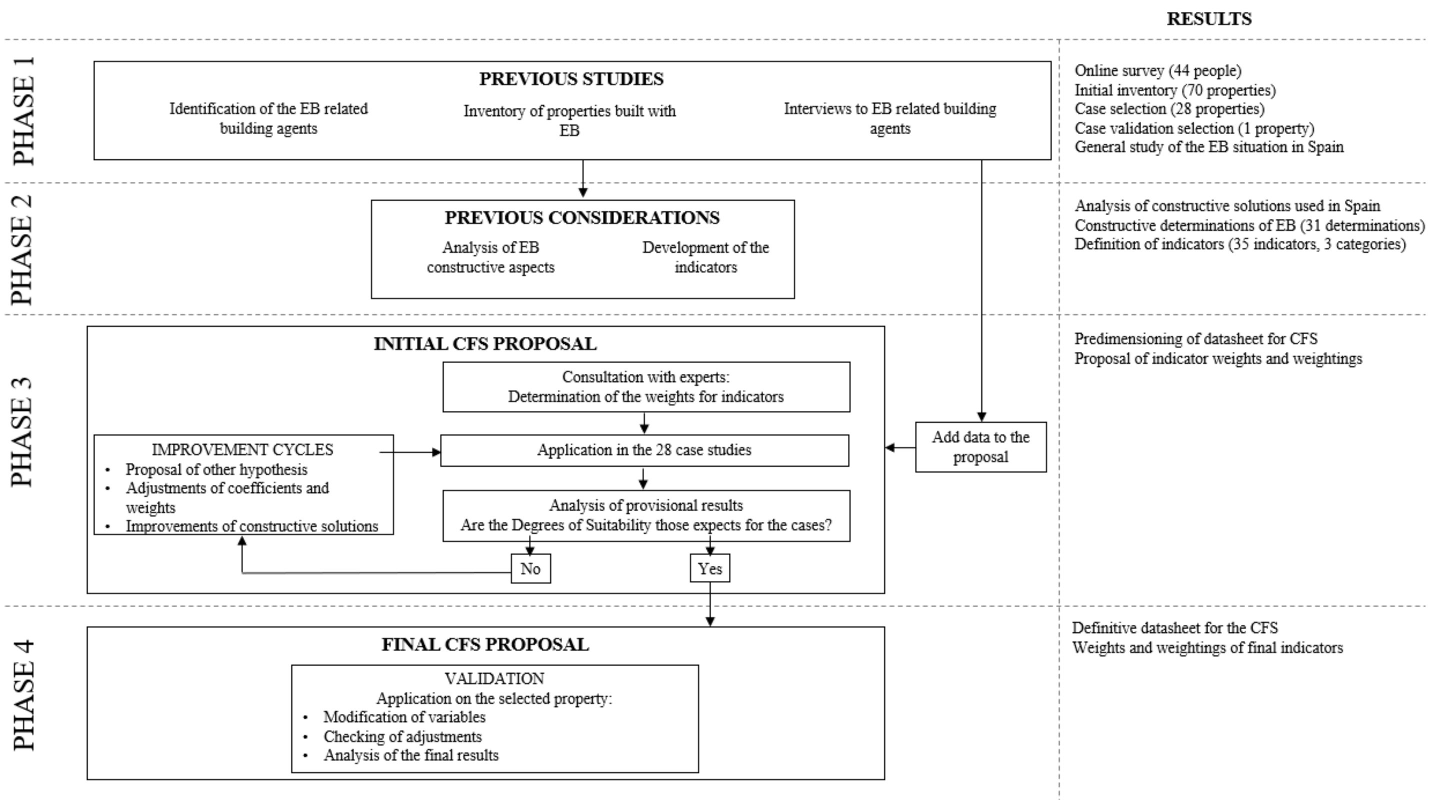

Figure 1. Methodological procedure set out to establish the CFS. Source: Preparation by the authors.

METHODOLOGICAL PROCEDURE OF THE RESEARCH. INDICATORS

The methodological process carried out to set up the tool, which will be called construction feasibility study (CFS), has been compartmentalized in the phases and contents that are detailed in Figure 1.

Starting from the inventory made on buildings that have used EB in their design in Spain, in a first phase, a set of 70 cases are chosen and analyzed, which correspond to 59 dwellings (residential use) and another 11 properties for tertiary, education or industrial use. Later, with fieldwork, the most relevant cases are chosen, leaving a total of 28 out of the 70 studied ones, which are divided in 15 cases of single-family residential use, 5 of multi-family use, 6 of third-party use and 2 educational buildings. In the second phase, the construction determinations associated to EB are cataloged (Table 1). In the third one, the tool is implemented in the 28 cases mentioned and, using improvement cycles, their optimal response is adapted. In the last phase, the operation of the CFS is validated in a case study not included in the 28 previous ones.

The first key aspect of CFS consists in setting out the construction determinations (second phase), which are organized considering the three categories developed in Table 1: the characteristics of the product (quality), the construction requirements (requirements of the construction system itself), and the external conditions (external actions). Thus, the product's quality considers the physical, chemical and mechanical characteristics of the EB, defined and/or stated by the manufacturer and established in the project. Secondly, the construction requirements are associated to the product to respond to certain aspects regarding compliance of the current regulations (Ministry of Development, 1999), fundamentally the structural stability of the factory and the inhabitability of the spaces. And, regarding the third category, it will have to consider the analysis of external actions that may affect the EB factory throughout its service life, which depend on the function that the wall has (load bearing or enclosure), its location and orientation, and the aggressiveness of the environment it is exposed to (Soronis, 1992).

Evaluación del bloque de tierra mediante un estudio de viabilidad constructiva (evc)
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Revista Hábitat Sustentable Vol. 10, N°. 2. ISSN 0719 - 0700 / Págs. 54 -69
https://doi.org/10.22320/07190700.2020.10.02.04

INDICATORS: Product quality (C-CA)			DETERMINATIONS: Product quality
C-CA-AF Physical aspects -002 -003 -004 -005 -006 -007 -008 -009	-001	Density	Apparent and dry density for sound requirements
	Mechanical resistance	Resistance to simple compression (UNE 41410)	
	Resistance to dry/wet cycles	Resistance to the cycles under severe outdoor conditions	
	Resistance to erosion	Resistance to the cycles under severe outdoor conditions	
	Capillary water absorption	Resistance to the cycles under severe outdoor conditions	
	Resistance to freeze/thaw cycles	Resistance assessed and/or declared in risk areas	
	Product's thermal properties	Characterization of thermal conductivity and specific heat	
	Water vapor permeability	Characterization of the permeability-resistance to water vapor	
	Adherence to shearing	Shear strength (load-bearing walls)	
C_CA-AQ Chemical aspects -002 -003	-001	Chemical characterization: earth and additives	Chemical stabilizers: cement, lime, plaster, silicate
	Water	Water: composition, salt and organic content	
	Reaction to fire	Piece's reaction to fire	
C-CA-AG Geometric aspects -002	-001	Dimensions and tolerances	Description of the type, dimensions, sizing and tolerances
	Appearance	Evenness, defects and cells	

INDICATORS: Constructive Requirements (C-RC)				DETERMINATIONS: Constructive requirements
C-RC-S Safety	Structural	-001.1	Load transmission	Type of wall, composition and thickness of the pointing, type of fiber, slenderness and load distribution
		-001.2	Transmission to the ground	
		-001.3	Bearing capacity	
		-001.4	Spatial configuration	Symmetries and rigidities of the wall and corners
		-001.5	Configuration of the openings	Opening distribution and size
	Fires	-002	Safety in case of fire	Evaluation and/or declaration of the reaction to fire
	Damage	-003	State of existing damage	
C-RC-H Inhabitability -002 -003		-001	Health and sanitation	Suction, absorption, open porosity or diffusiveness of water vapor
		Sound insulation	Sound reduction index or airborne sound insulation value	
		Thermal behavior	Evaluation of the wall's thermal resistance	

INDICATORS: External actions (C-AE)				DETERMINATIONS: External actions
C-AE-F Physical	Meteorology	-001.1	Rain	Rainfall intensity, prevailing winds and designed protections
		-001.2	Wind	
		-001.3	Temperature	
	Land	-002	Land morphology	Drainage capacity of surrounding land
	Natural agents	-003	Seismic	Local seismic risk
C-AE-M Mechanical	Anthropic agents	-001	Use of the space	Impact of human activities
C-AE-Q Physical-chemical	Organisms	-001	Vegetation and animals..	Impact of animal and vegetation activities
	Anthropic agents	-002	Environment	Impact of human activities that contaminate the air or water
	Natural agents of the environment and the land	-003.1	Land humidity	Impact of phreatic water
		-003.2	Environmental humidity	Risk of condensation
		-003.3	Solar radiation	Degradation by UV radiation

Table 1. Determinations considered and associated indicators. Source: Preparation by the Authors.

The determinations presented in Table 1 are used to establish a total of 35 associated indicators. The indicators are identified using a code (C-CA: quality constructive indicators; C-RC: constructive requirements; C-AE: external actions) and are evaluated using numeric values based on concepts and appreciations. The quantitative and/or qualitative valuation of each indicator is called Technical Assessment Level (NET in Spanish) and requires its basic definition following: (I) a description of its three possible levels (1, 2 or 3), and (II) the references and sources used, as suggested by the UNE 21929-1:2010 (AENOR, 2009) to define sustainability indicators for buildings. The three levels of indicators are expressed as: 1 (low assessment level, negative valuation); 2 (medium level, moderate valuation); and 3 (high level, positive valuation) (Figure 2).

METHODOLOGICAL PROPOSAL FOR THE CFS

The CFS is designed to be applied in the first stage of preparation of the architectonic project. In this phase, the goal is to consider possible strategies in the constructive design of the enclosure non-load bearing wall. The assessment procedure (Figure 3) comprises three differentiated stages: data entry, establishing indicator levels, and evaluation which, for its part, is developed in two concatenated stages.

In the first stage, the information sources having been considered, the constructive determinations of the case study are compiled and classified following

Concept: Resistance to dry/wet cycles **Code: C-CA-AF-003**

Root: Product quality>Physical aspects

Parameter description: Knowing beforehand the EB's resistence to dry and wet cycles, will provide data about possible constructive solutions that do not imply a deterioration of the material when facing severe exposure.

Technical considerations:
Is it interesting for us to know about the resistance to dry and wet cycles?

In the test, on facing severe exposure, the wall must be capable of bearing six dry and wet cycles without seeing a series of conditions (specific test of UNE 41410:2008).

The deterioration caused by these cycles on the survey, means the material decomposes more quickly (Falceto, 2012).

Levels:

Color	Level	Explanation
Low	1	**External production**, the manufacturer does not state any aspect about the resistance to dry and wet cycles. In the onsite **production**, the declaration of resistance to dry and wet cycles will not be possible.
Medium	2	**External production**, the manufacturer does state about the resistance to dry and wet cycles. In the onsite **production**, the declaration of resistance to dry and wet cycles will be possible, but not its certification.
High	3	**External production**, the manufacturer does state and certify the resistance to dry and wet cycles. In the onsite **production**, the declaration and certification of the product will be possible.

Standard:
Page 14 - UNE 41410:2008 - (**UNE 41410**, 2008)
ASTM D599: 1989 - Wetting and drying test.
Reference:
(Guettala, Abibsi, & Houari, 2006)

Figure 2. Basic definition of the NET for the indicator of resistance to wet/dry cycles. Source: Preparation by the authors based on the UNE 41410 (2008) and ASTM D559 (1989) standards.

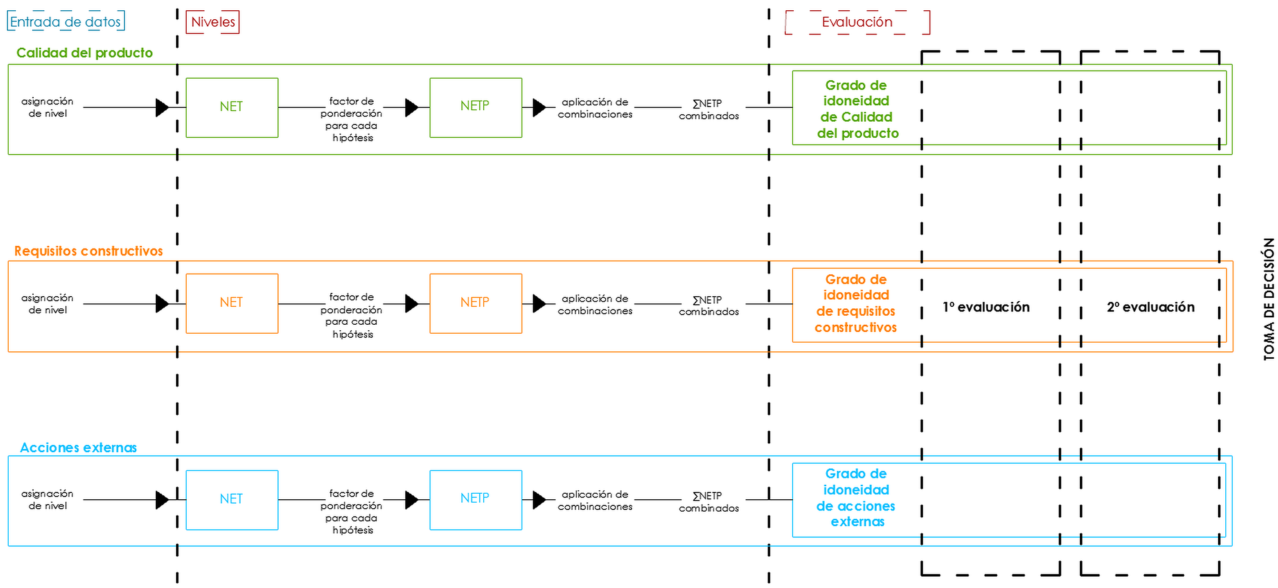

Figure 3. CFS procedure stages. Source: Preparation by the Authors.

	Aspects of application of EB on the wall										
	Foundation	Base	Openings	Lintel	Jambs	Sill	Finishes	Inside	Outside	Installation	Crown
	Weighting by weight (Wi)										
	W1	W2		W3	W4	W5		W6	W7	W8	W9
C-CA Product quality											
C-CA-AF-001 Density	10,00	6,90		4,35	4,35	4,55		4,55	4,76	8,00	10,53
C-CA-AF-002 Mechanical resistance	10,00	6,90		13,04	4,35	4,55		4,55	4,76	12,00	10,53
C-CA-AF-003 Resistance to dry/wet cycles	5,00	6,90		4,35	8,70	9,09		9,09	9,52	4,00	5,26
C-CA-AF-004 Resistance to erosion	5,00	10,30		4,35	4,35	4,55		9,09	4,76	8,00	5,26
C-CA-AF-005 Capillary water absorption	15,00	6,90		4,35	8,70	9,09		9,09	9,52	8,00	5,26
C-CA-AF-006 Resistance to freeze/thaw cycles	10,00	6,90		4,35	4,35	4,55		4,55	9,52	4,00	5,26
C-CA-AF-007 Product's thermal properties	5,00	6,90		8,70	8,70	9,09		4,55	4,76	4,00	5,26
C-CA-AF-008 Water vapor permeability	5,00	6,90		8,70	8,70	9,09		13,64	14,29	4,00	5,26
C-CA-AF-009 Adherence	5,00	6,90		4,35	4,35	4,55		4,55	4,76	12,00	5,26
C-CA-AO-001 Characteristics of constituent parts - Stabilizers	5,00	6,90		4,35	4,35	4,55		9,09	4,76	8,00	10,53
C-CA-AO-002 Water as constituent part	5,00	6,90		4,35	4,35	4,55		4,55	4,76	8,00	5,26
C-CA-AO-003 Reaction to fire	5,00	6,90		13,04	13,04	9,09		13,64	14,29	4,00	10,53
C-CA-AG-001 Dimensions and tolerances	5,00	6,90		13,04	13,04	13,64		4,55	4,76	8,00	10,53
C-CA-AG-002 Appearance	10,00	6,90		8,70	8,70	9,09		4,55	4,76	8,00	5,26
TOTALS (%)	100,00	100,00		100,00	100,00	100,00		100,00	100,00	100,00	100,00
C-RC Constructive requirements											
C-RC-S-001.1 Load transmission	17,65	15,00		11,11	7,69	7,14		5,88	6,67	15,00	10,53
C-RC-S-001.2 Transmission to earth	17,65	5,00		11,11	7,69	7,14		5,88	6,67	15,00	10,53
C-RC-S-001.3 Load-bearing capacity	17,65	15,00		16,67	7,69	7,14		5,88	6,67	10,00	15,79
C-RC-S-001.4 Spatial configuration	5,88	10,00		11,11	15,38	14,29		11,76	20,00	5,00	10,53
C-RC-S-001.5 Openings	5,88	5,00		16,67	23,08	21,43		5,88	13,33	10,00	5,26
C-RC-S-002.1 Fire safety	5,88	10,00		11,11	7,69	7,14		17,65	6,67	10,00	10,53
C-RC-S-003.1 Stabilization of existing damages	11,76	10,00		5,56	7,69	7,14		11,76	6,67	10,00	10,53
C-RC-H-001.1 Environmental protection, health and safety	5,88	10,00		5,56	7,69	7,14		11,76	6,67	5,00	5,26
C-RC-H-001.2 Noise insulation	5,88	10,00		5,56	7,69	7,14		11,76	13,33	10,00	10,53
C-RC-H-001.3 Thermal behavior	5,88	10,00		5,56	7,69	14,29		11,76	13,33	10,00	10,53
TOTALS (%)	100,00	100,00		100,00	100,00	100,00		100,00	100,00	100,00	100,00
C-AE External actions											
C-AE-F-001.1 Rain	9,52	14,29		7,69	20,00	20,00		6,67	15,79	7,69	13,33
C-AE-F-001.2 Wind	4,76	9,52		7,69	6,67	6,67		6,67	15,79	7,69	6,67
C-AE-F-001.3 Temperature	4,76	4,76		7,69	6,67	6,67		6,67	5,26	7,69	6,67
C-AE-F-002.1 Land	14,29	9,52		7,69	6,67	6,67		6,67	5,26	7,69	6,67
C-AE-F-003.1 Seismic	14,29	9,52		15,38	13,33	13,33		13,33	10,53	15,38	13,33
C-AE-M-001 Use of the space by animals, people...	9,52	9,52		7,69	6,67	6,67		13,33	10,53	7,69	6,67
C-AE-O-001.1 Biological agents	9,52	9,52		7,69	6,67	6,67		6,67	5,26	7,69	6,67
C-AE-O-002.1 Type of environment	9,52	9,52		7,69	6,67	6,67		13,33	10,53	7,69	6,67
C-AE-O-003.1 Land humidity	14,29	9,52		7,69	6,67	6,67		6,67	5,26	15,38	6,67
C-AE-O-003.2 Environmental humidity	4,76	9,52		15,38	13,33	13,33		13,33	10,53	7,69	13,33
C-AE-O-003.3 Solar radition	4,76	4,76		7,69	6,67	6,67		6,67	5,26	7,69	13,33
TOTALS (%)	100,00	100,00		100,00	100,00	100,00		100,00	100,00	100,00	100,00
Note:		Slight			Moderate				Decisive		

Figure 4. Result of the survey to experts to establish the weight averages (Wi) in each wall aspect of all the indicators. Source: Preparation by the Authors.

Combinations (j)	Indicators with reduction of valuation by combination			K* coefficient for the aspects (i)								
				O-01A	O-01B	O-01C-01	O-01C-02	O-01C-03	O-01D-01	O-01D-02	O-01E	O-01F
	Quality (CA)	Constructive Requirements (RC)	External actions (AE)	Foundation	Base	Lintel	Jambs	Sill	Inside	Outside	Installation	Crown
Nº 01			C-AE-F-001.1/ C-AE-F-001.2	0	**0,5**	**0,5**	**0,5**	**0,5**	0	**0,5**	**0,5**	**0,5**
Nº 02			C-AE-F-001.1/ C-AE-F-002.1/ C-AE-Q-003.1/ C-AE-M-001	**0,5**	**0,5**	0	0	0	0	0	0	0
Nº 03			C-AE-Q-001.1	**0,5**	**0,5**	**0,5**	**0,5**	**0,5**	**0,5**	**0,5**	0	**0,5**
Nº 04		C-RC-S-001.4	C-AE-F-002.1/ C-AE-F-003.1	0	0	**0,5**	**0,5**	0	0	0	0	**0,5**
Nº 05		C-RC-ES-001	C-AE-Q-003.2	0	0	**0,5**	**0,5**	**0,5**	**0,5**	**0,5**	0	0
Nº 06	C-CA-AF-005/ C-CA-AF-008	C-RC-ES-001	C-AE-F-001.3/ C-AE-Q-003.2	0	**0,5**	**0,5**	**0,5**	**0,5**	0	0	0	**0,5**
Nº 07		C-RC-S-001.1/ C-RC-S-001.4/ C-RC-S-001.5		0	**0,5**	**0,5**	0	0	0	0	0	**0,5**

(*) K=1 for the rest of the indicators not included in the combinations

Figure 5. Critical combinations following the survey to experts and their Kj weight coefficients considering the established aspects. Source: Preparation by the authors.

the categories of Table 1, which is used to later value the associated indicators, following the *NET* for each one of the 35 indicators of the three categories. It is worth clarifying that on each indicator being of a different nature and the application settings within a wall being different, not all the indicators will have the same degree of influence on the assessment, as such their values must not be added directly. For this reason, weighing methods are established, following the UNE-ISO/TS 21929 (AENOR, 2009), through the application of correction coefficients or weights, prepared from surveys to experts (see Figure 1, phase 3), emphasizing in the valuation of the degree of determination of each indicator, following nine application aspects of the EB defined as enclosure elements (these consider: foundation, wall base, parts of an opening – lintel, jambs, sill -, finishing – indoor and outdoor – installations and crowning of the wall) (Figure 4). Three types of indicators are also included in these surveys, determined considering the associated weights: decisive, moderate or slight. The ranges of the *NET* (1 to 3) are weighted in terms of the relationship between the proposed indicators and the nine defined aspects of the wall. Thus, the *NET* will reduce or maintain its value proportionally through the product with the coefficient, obtaining the weighted technical assessment level *(NETP)*

Therefore, as there are nine aspects, just as Figure 4 shows, nine sets of NETP are obtained, after applying the following equation [1]:

$$NETP_i = \frac{NET \times W_i}{100} \quad [1]$$

where W_i is the weight for each one of the nine aspects studied.

The surveys to experts are also used to consider which circumstances are the most adverse when there are certain critical combinations. Starting from these, seven critical combinations of indicators that reduce the valuations of the *NETPi* are established. In this way, for each one of the nine aspects, some of the seven possible combinations that are outlined in Figure 5 would develop. On establishing the condition that, for *NET* < 3 of the indicators associated to the combinations, the valuations of their corresponding *NETP* will be reduced 50% through the K_j coefficient, leaving the weighing of *NET* following equation [2].

$$NETP_{i,j,q} = \frac{NET_q \times W_i}{100} \times K_j \quad [2]$$

Next, all the *NETP* of each block are added (C-CA, C-RC and C-AE) and by combination, within each one of the nine aspects of the wall, as is detailed in the graph of Figure 6. The degree of suitability of each aspect (hereinafter GI_i) would correspond to the minimum of the combinations made, obtaining with the average of the nine GI_i, the *GI* for each block (C-CA, C-RC, C-AE), through which the two levels of assessment will be developed.

Revista Hábitat Sustentable Vol. 10, N°. 2. ISSN 0719 - 0700 / Págs. 54 -69
https://doi.org/10.22320/07190700.2020.10.02.04

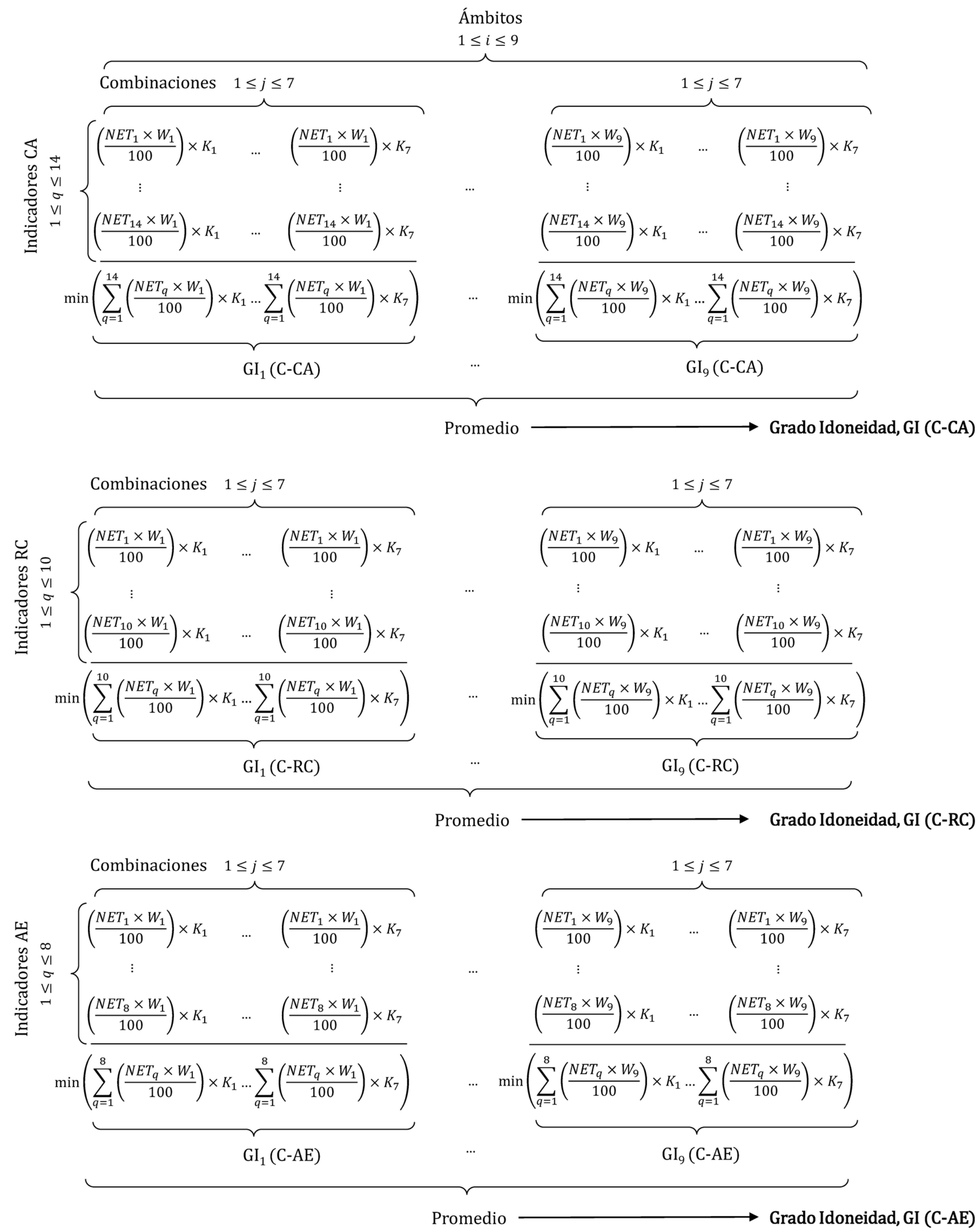

Figure 6. Sequence of stages in the NET assessment. Source: Preparation by the authors.

The first assessment level of the *GI* allows obtaining an affirmative ("Suitable") or negative ("Unsuitable") response on the constructive feasibility of the EB. For this, a final criterion is established depending on the *GI*, evaluated as "Suitable" as long as the average *GI* of the three blocks (*GI(C-CA)* = 1.5, *GI(C-RC)* = 2.3, *GI(C-AE)* = 2.5) is higher than or equal to the preset *GI* thresholds (also see Figure 11). The rating of "Suitable" implies that the constructive solutions are feasible from a constructive point of view and could be implemented in the execution project. However, the negative response of "Unsuitable" would imply making a second assessment level.

In that second assessment level, the indicators are studied in greater detail based on two lines of analysis, to identify deficiencies and to propose improvements. The first analysis corresponds to the product's quality

Aspect	Block (*)	GI low		GI moderate		GI high	
		Min	Max	Min	Max	Min	Max
Foundation	RC	0	2,32	2,33	2,69	2,7	3
	AE	0	2,32	2,33	2,69	2,7	3
Wall base	RC	0	2,29	2,3	2,53	2,54	3
	AE	0	2,1	2,11	2,59	2,6	3
Openings - Lintel	RC	0	2,18	2,19	2,59	2,6	3
	AE	0	1,99	2	2,59	2,6	3
Openings - Jambs	RC	0	2,18	2,19	2,58	2,59	3
	AE	0	1,99	2	2,59	2,6	3
Openings - Sill	RC	0	2,24	2,25	2,58	2,59	3
	AE	0	1,98	1,99	2,59	2,6	3
Finish - Indoor	RC	0	2,25	2,26	2,45	2,46	3
	AE	0	1,99	2	2,58	2,59	3
Finish - Outdoor	RC	0	2,32	2,33	2,58	2,59	3
	AE	0	2,19	2,2	2,58	2,59	3
Technical resources	RC	0	2,29	2,3	2,7	2,71	3
	AE	0	2,29	2,3	2,7	2,71	3
Crown	RC	0	2,39	2,4	2,59	2,6	3
	AE	0	2,18	2,19	2,58	2,59	3
Partition	RC	0	2,29	2,3	2,59	2,6	3
	AE	0	2,29	2,3	2,69	2,7	3

(*) RC: Constructive requirements; AE: external actions

Figure 7. Classification of GI according to the intervals established for the second assessment level. Source: Preparation by the Authors.

indicators, as such the corresponding *NET* are cross checked with the demands of the current standards in force (essentially UNE 41410:2008) and shortcomings are detected in the technical specifications of the manufacturer's statements, which, at the same time, can be resolved or at least proposals of alternative measures could be allowed. For this purpose, some conditional algorithms have been designed in the CFS that link these indicators with the data entry values related to the product's quality. The second analysis is focused on the GI_i of the constructive requirements and on the external actions that affect all aspects of the wall where EB is used. In this case, three classifications of the GI_i ranges have been established: optimal (green), moderate (yellow) or low (red). This classification is made from the GI_i intervals of the 28 case studies implemented (Figure 7). Depending on the classification of each GI_i, possible solutions can be established to improve the aspects considered as deficient.

Once the methodology procedure of the CFS is developed, a variation is made through the implementation of the method on a case study not included in the list of the 28 ones chosen as the basis to make the tool.

VALIDATION AND RESULTS

The goal of the proposed tool's validation is to verify that the procedure is suitable for the constructive assessment of EB walls as part of an architectonic project. With said purpose, it is confirmed whether the results of the CFS or any case study are those estimated in terms of their *GI*. To validate the CFS, a sufficiently sized building is chosen (approximately 700m^2 built) with available technical documentation, where the constructive solutions are varied and that uses EB with technical certification on the enclosure walls.

With these starting conditions, the La Font del Rieral Municipal Primary School in Santa Eulàlia de Ronçana (Barcelona) is chosen, designated as BAR-001. In one sector, CEB are used, with a size of 29x14.5x9.5 cm, from a manufacturer that provides product datasheets, where the regulatory requirements are justified, although without official standardization. The main characteristics of the walls' constructive solutions appear on the building's south-facing façade, comprised by a double CEB sheet load-bearing wall (each sheet with a thickness of 14.5 cm), anchored to each other with zinc-coated steel pins, with a natural cork insulation layer (2 cm) and inner air chamber (5 cm). These walls, towards the inside have a visible CEB with a baseboard covered with laminate panels up to the window sills; and on the outside, these are treated with water repellant that is coated with lime and cement mortar. The openings are designed with suitably waterproofed wood carpentry. The support of the load-bearing wall to the foundation is made using cement mortar block course, connected with corrugated metal bars to the reinforced concrete strip footing; the waterproofing sheet is placed on the base of the CEB wall above

Product quality		
Product		**CEB - Bioterre**
Production	Onsite / external	External
Type of EB and block composition foreseen	Type of stabilizer	Cement
	Declaration of stabilizer	Yes
	Certification of stabilizer	Yes
	Density foreseen	Yes
	Use of fibers	No
	Water composition indication	No
	Organic matter or salts.	No
Declaration of data	Density	Yes
	Compressive strength	Yes
	Resistance to dry/wet cycles	Yes
	Resistance to erosion	Yes
	Capillary water absorption	Yes
	Resistance to freeze/thaw cycles	Yes
	Product's thermal properties	Yes
	Water vapor permeability	Yes
	Fire reaction	Yes
	Dimensions	Yes
	Tolerances	Yes
	Evenness	Yes
	Defects	Yes
	Cells	Yes
Certification through standardized tests	Density	Yes
	Compressive strength	Yes
	Resistance to dry/wet cycles	Yes
	Resistance to erosion	Yes
	Capillary water absorption	Yes
	Resistance to freeze/thaw cycles	Yes
	Product's thermal properties	Yes
	Water vapor permeability	Yes
	Fire reaction	Yes
External agents		
Environmental aspects	Average rainfall in area (CTE)	III
	Prevailing wind of the area	East and west
	Wind (km/h)	-
	Wind Area	C
	Minimum temperature	<0ºC
	Environmental humidity	>70%
	Risk of microorganisms	Yes
Aspects of the land	Description of the land profile considering the intervention site	Slightly sloped
	Height of the phreatic level	Unknown
	Ag coefficient of the area (Seismic)	0.09
Heritage aspects	Catalog	No
	Specific standards	No
	Degree of protection	-
	Sustainability strategies	No
	Specific construction standards	No
Others	Type of surrounding vegetation	Sheet ending on south facade which provides shade in summer and light, in winter
	Type of possible contamination	None
	Use of surrounding space	Playground

Constructive requirements		
General characteristics of the property	Height	3 meters approx.
	Nº of floors	1
	Spatial composition	Non-symmetrical / curve
	Building use	Education
Characteristics of the wall	Location of block on facade	Outside
	Type of wall or visible face covering.	Covering
	Type of mortar being used.	Lime mortar
	Wall composition.	Double 30 cm CEB wall with chamber and 2 cm natural cork insulation
	Height foreseen of wall support.	15 cm
	Type of wall support on the foundation.	Wall elevated by concrete block and anchored to the foundation
	Foundation foreseen.	Concrete strip footing supported directly on firm ground
	Wall bracing	Crowning beam
	Slenderness.	2.5 meters high
	Symmetric or irregular volume.	Irregular
	Openings	With openings
	Thickness foreseen.	30 cms
	Continuity of the elements	Yes
	Joints foreseen	Yes
	Analysis foreseen of holding mortar used	Yes
Protection elements	Use of baseboard	No
	Use of cornice	Yes
General constructive characteristics	Structural typology	Load-bearing
	Constructive system: load or non-load bearing	Walls
	Structure: identification of loads and overloads 1	Vertical
	Structure: identification of loads and overloads 2	N/A
Requirements	Severe exposure?	No
	Visible face?	No/Yes
	Thermal insulation requirements?	Yes
	External parameter?	Yes
	Noise requirements	Yes
	Structural requirements	Yes
	Fire resistance requirements	Yes

Name	**Escuela Santa Eulalia de Ronçana**	**BAR-001**
Aspects		
Foundation		No
Wall base		Yes
Openings in the wall	Lintel	Yes
	Jambs	Yes
	Sill	Yes
Finishes	Inside	Yes
	Outside	Yes
Installation of technical resources		Yes
Wall crown		Yes

Figure 8. Initial data entry for BAR-001 case study. Source: Preparation by the authors.

ground level. A reinforced concrete truss beam crowns the wall, where the roof's sawn wooden beam rests. The project considers the requirements of the Technical Building Code (Spain).

Upon analyzing the available information on the project, data entry is made (Figure 8), looking to obtain an optimal CFS response for the first assessment level, given that the starting parameters for the three blocks considered are favorable. All indicators have a *NET* of three, except for C-RC-S-001.4 (Spatial configuration), C-RC-S-0021 (Fire safety) and C-AE-F-001.3 (Temperature), which are valued with two; and C-CA-AQ-002 (water as constituent part) which has a value of 1, on not having proof of the tempering water requirements, as per UNE 41410.

The first result of the CFS (Figure 9) shows the *NETP* and GI_i corresponding to the different aspects of the studied wall, as well as the average *GI*, which makes it possible to pass the first assessment level. The initial hypothesis is thus confirmed, where it was estimated

	Initial Hypothesis										Hypothesis 1	Hypothesis 2
	EB application aspects on the wall											
	Foundation	Base	Lintel	Jambs	Sill	Inside	Outside	Installation	Crown	Average GI	Average GI	Average GI
Indicator												
C-CA-AF-001 Density	0,00	0,21	0,13	0,13	0,14	0,14	0,14	0,24	0,32			
C-CA-AF-002 Mechanical resistance	0,00	0,21	0,39	0,13	0,14	0,14	0,14	0,36	0,32			
C-CA-AF-003 Resistance to dry/wet cycles	0,00	0,21	0,13	0,26	0,27	0,27	0,29	0,12	0,16			
C-CA-AF-004 Resistance to erosion	0,00	0,31	0,13	0,13	0,14	0,27	0,14	0,24	0,16			
C-CA-AF-005 Capillary water absorption	0,00	0,21	0,13	0,26	0,27	0,27	0,29	0,24	0,16			
C-CA-AF-006 Resistance to freeze/thaw	0,00	0,21	0,13	0,13	0,14	0,14	0,29	0,12	0,16			
C-CA-AF-007 Product's thermal properties	0,00	0,21	0,26	0,26	0,27	0,14	0,14	0,12	0,16			
C-CA-AF-008 Water vapor permeability	0,00	0,21	0,26	0,26	0,27	0,41	0,43	0,12	0,16			
C-CA-AF-009 Adherence	0,00	0,21	0,13	0,13	0,14	0,14	0,14	0,36	0,16			
C-CA-AO-001 Characteristics of constituent	0,00	0,21	0,13	0,13	0,14	0,27	0,14	0,24	0,32			
C-CA-AO-002 Water as constituent part	0,00	0,07	0,04	0,04	0,05	0,05	0,05	0,08	0,05			
C-CA-AO-003 Reaction to fire	0,00	0,21	0,39	0,39	0,27	0,41	0,43	0,12	0,32			
C-CA-AG-001 Dimensions and tolerances	0,00	0,21	0,39	0,39	0,41	0,14	0,14	0,24	0,32			
C-CA-AG-002 Appearance	0,00	0,21	0,26	0,26	0,27	0,14	0,14	0,24	0,16			
GI_i (C-CA)	**0,00**	**2,86**	**2,91**	**2,91**	**2,91**	**2,91**	**2,90**	**2,84**	**2,89**	**2,89**	**2,52**	**2,89**
C-RC-S-001.1 Load transmission	0,00	0,45	0,33	0,23	0,21	0,18	0,20	0,45	0,32			
C-RC-S-001.2 Transmission to ground	0,00	0,15	0,33	0,23	0,21	0,18	0,20	0,45	0,32			
C-RC-S-001.3 Load-bearing capacity	0,00	0,45	0,50	0,23	0,21	0,18	0,20	0,30	0,47			
C-RC-S-001.4 Spatial configuration	0,00	0,20	0,22	0,31	0,29	0,24	0,40	0,10	0,21			
C-RC-S-001.5 Configuration of openings	0,00	0,15	0,50	0,69	0,64	0,18	0,40	0,30	0,16			
C-RC-S-002 .1 Fire safety	0,00	0,20	0,22	0,15	0,14	0,35	0,13	0,20	0,21			
C-RC-S-002.2 State of existing damages	0,00	0,30	0,17	0,23	0,21	0,35	0,20	0,30	0,32			
C-RC-H-001.1 Environmental protection.	0,00	0,30	0,17	0,23	0,21	0,35	0,20	0,15	0,16			
C-RC-H-001.2 Noise insulation	0,00	0,30	0,17	0,23	0,21	0,35	0,40	0,30	0,32			
C-RC-H-001.3 Thermal insulation	0,00	0,30	0,17	0,23	0,43	0,35	0,40	0,30	0,32			
GI_i (C-RC)	**0,00**	**2,80**	**2,78**	**2,77**	**2,79**	**2,71**	**2,73**	**2,85**	**2,79**	**2,78**	**2,70**	**2,20**
C-AE-F-001.1 Rainfall	0,00	0,43	0,23	0,60	0,60	0,20	0,47	0,23	0,40			
C-AE-F-001.2 Wind	0,00	0,29	0,23	0,20	0,20	0,20	0,47	0,23	0,20			
C-AE-F-001.3 Temperature	0,00	0,10	0,15	0,13	0,13	0,13	0,11	0,15	0,13			
C-AE-F-002.1 Land profile	0,00	0,29	0,23	0,20	0,20	0,20	0,16	0,23	0,20			
C-AE-F-003.1 Seismic	0,00	0,29	0,46	0,40	0,40	0,40	0,32	0,46	0,40			
C-AE-M-001 Use of space by animals.	0,00	0,29	0,23	0,20	0,20	0,40	0,32	0,23	0,20			
C-AE-O-001.1 Biological agents	0,00	0,29	0,23	0,20	0,20	0,20	0,16	0,23	0,20			
C-AE-O-002.1 Activities of man	0,00	0,29	0,23	0,20	0,20	0,40	0,32	0,23	0,20			
C-AE-O-003.1 Land humidity	0,00	0,29	0,23	0,20	0,20	0,20	0,16	0,46	0,20			
C-AE-O-003.2 Environmental humidity	0,00	0,29	0,46	0,40	0,40	0,40	0,32	0,23	0,40			
C-AE-O-003.3 Solar Radiation	0,00	0,14	0,23	0,20	0,20	0,20	0,16	0,23	0,40			
GI_i (C-AE)	**0,00**	**2,95**	**2,92**	**2,93**	**2,93**	**2,93**	**2,95**	**2,92**	**2,93**	**2,93**	**2,93**	**2,93**
GI (Feasibility)										**Accepted**	**Accepted**	**Not accepted**

Figure 9. Results of NETP and GI (first assessment level) of the chosen case study. Source: Preparation by the authors.

that the type of EB used was viable for the project's solutions.

In the second assessment level, all requirements are met (Figure 10) for the block in terms of quality indicators (C-CA). Regarding the GI_i of the C-RC and C_AE blocks, values close to 3 are determined and, therefore, they also show an excellent constructive viability for the proposed constructive solutions.

Below, in the interest of gaining different responses of the tool, hypothetical constructive variations are assigned. Thus, variants are established, where it is analyzed which *GI* is not suitable, and it is verified which solutions are proposed. The first hypothesis focuses on altering the product's quality, assuming that it does not have certain technical declarations: resistance to wetting cycles (indicator C-CA-AF-003, *NET*=1), resistance to erosion (indicator C-CA-AF-004, *NET*=1) and resistance to freeze-thaw cycles (indicator C-CA-AF-006, *NET*=1). In addition, it is assumed that the external sheet of the CEB wall is uncoated, changing the entry data considering these same criteria. Consequently, the result of the second assessment level in terms of quality, reflects a non-compliance of the three aspects required by UNE 41410, which would guarantee an optimal quality for an elevated degree of exposure; capillary water absorption, resistance to freeze/thaw cycles and water vapor permeability tests. The GI_i (C-RC) are slightly changed on having altered the C-RC-H-001 indicator, that controls the hygroscopic response of the enclosure, now exposed. Meanwhile the GI_i (C-AE) are unaltered on not having changed the conditions (Figure 10). It can also be confirmed that these changes do not imply a non-compliance of the first assessment (Figure 9).

SUITABILITY REGARDING PRODUCT QUALITY AND REQUIREMENTS				
Product quality indicators	**Requirements - UNE 41410:2008**	**Initial**	**Hypothesis 1**	**Hypothesis 2**
C-CA-AF-001 Density	For noise requirements	Complies	Complies	Complies
C-CA-AF-002 Mechanical Resistance C-CA-AF-009 Adherence to shearing	Structural requirements. Compressive strength	Complies	Complies	Complies
C-CA-AF-003 Resistnace to dry/wet cycles	Declaration/test required with severe exposure	Complies	Complies	Complies
C-CA-AF-004 Resistance to erosion	Declaration/test required with severe exposure	Complies	Complies	Complies
C-CA-AF-005 Capillary water absorption	Declaration/test required with visible walls	Complies	**Does not comply**	Complies
C-CA-AF-006 Resistance to freeze/thaw cycles	Declaration/test required with visible walls	Complies	**Does not comply**	Complies
C-CA-AF-007 Product's thermal properties	Thermal requirements. Thermal conductivity (λ)	Complies	Complies	Complies
C-CA-AF-008 Water vapor permeability	Declaration/test required with outside walls	Complies	**Does not comply**	Complies
C-CA-AQ-001 Chemical characterization: earth and additives	Declaration/test for presence of microorganisms	Complies	Complies	Complies
C-CA-AQ-002 Water	Declaration/test of organic contents, salts and pH	Complies	Complies	Complies
C-CA-AQ-003 Reaction to fire	Declaration of fire reaction rating	Complies	Complies	Complies

SUITABILITY ABOUT CONSTRUCTIVE REQUIREMENTS AND EXTERNAL ACTIONS								
	Degrees of Suitability		**GI_i (C-RC)**	**GI_i (C-AE)**	**GI_i (C-RC)**	**GI_i (C-AE)**	**GI_i (C-RC)**	**GI_i (C-AE)**
Aspects of the Wall	O-01A	Foundation	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**
	O-01B	Base	**2,80**	**2,95**	**2,70**	**2,95**	**2,10**	**2,95**
	O-01C-01	Lintel	**2,78**	**2,92**	**2,72**	**2,92**	**1,89**	**2,92**
	O-01C-02	Jambs	**2,77**	**2,93**	**2,69**	**2,93**	**2,38**	**2,93**
	O-01C-03	Sills	**2,79**	**2,93**	**2,71**	**2,93**	**2,43**	**2,93**
	O-01D-01	Indoor	**2,71**	**2,93**	**2,59**	**2,93**	**2,53**	**2,93**
	O-01D-02	Outdoor	**2,73**	**2,95**	**2,67**	**2,95**	**2,47**	**2,95**
	O-01E	Installation	**2,85**	**2,92**	**2,80**	**2,92**	**2,50**	**2,92**
	O-01F	Crown	**2,79**	**2,93**	**2,74**	**2,93**	**2,16**	**2,93**

Figure 10. Results of the second assessment level for the case study. Source: Preparation by the authors.

In the second hypothesis, starting from the initial status, some constructive solutions are altered, which imply an eccentric transmission of loads on the foundation (C-RC-S-001.1, *NET*=2), an unsuitable wall slenderness (>1:10), and the presence of elements that reduce the wall's load-bearing capacity (for example, unsuitable filling mortar of joints) (C-RC-S-001-3, *NET*=2). In addition, the openings would have dimensions that are greater than those recommended for building with earth (Walker, 2001) (C-RC-S-001.5, *NET*=1). As for the first assessment level (Figure 9), a non-compliance will be seen, as the GI_i (C-RC) is lower than the established mean (2.3). Considering the second level, the requirements of UNE 41410 are met, as the product's quality is not altered (Figure 10). Likewise, as the external circumstances do not alter either, the GI_i (C-AE) continue to be favorable. However, the GI_i (C-RC) show low or medium valuations, specifically in the most critical aspects: base, crown and lintels, so it would be necessary to review the proposed constructive solutions, fundamentally in these aspects.

Finally, in summary, Figure 11 reflects the results obtained for the first assessment level of all the case studies used in the design of this tool.

It is concluded that, of the 28 cases analyzed, diverse results are obtained that can reproduce, at a general level, certain common guidelines in a building project. Consequently, despite these cases not being statistically representative, they allow generating a valid feedback tool. The compliance of the first assessment level occurs in most cases, although the causes of pathologies are much more diverse and reflect that the problems reside, be it in the quality of the product supplied or in the adverse conditions of the context (or even in both simultaneously).

CONCLUSIONS

The methodological procedure of the research has allowed validating the operation of the CFS tool to assess the design determinations of EB walls, as the results obtained are coherent with the constructive reality of the case study used. In this way, CFS could be implemented in any architectonic design that uses EB, which would help its use with a better technical support that is capable of ensuring better results and favoring the use of materials with a low environmental impact, such as this product.

It is insisted that the use of indicators, with an objective weighting that fits the constructive reality and that of the material, contributes to technical decision-making being impartial and objective, and not influenced by social prejudices or by a lack of knowledge regarding use of EB.

	Degree of Suitability (GI)			
	C-CA Product quality	C-RC Constructive requirements	C- AE External actions	
GI mean value	1,5	2,3	2,5	Results 1st assessment level
Case studies				
Andalucía				
ALM-001	2,31	2,83	2,80	**Suitable**
ALM-002	2,52	2,40	2,49	**Not Suitable**
GRA-001	1,27	2,56	2,52	**Not Suitable**
MAL-001	1,28	2,11	1,81	**Not Suitable**
SEV-001	2,52	2,83	2,87	**Suitable**
SEV-002	1,16	2,60	2,87	**Not Suitable**
SEV-003	1,17	2,69	2,50	**Not Suitable**
Aragón				
ZAR-001	1,42	2,72	2,92	**Not Suitable**
ZAR-002	2,52	2,72	2,72	**Suitable**
HUE-001	2,52	2,83	2,72	**Suitable**
Baleares				
BAL-001	3,00	3,00	3,00	**Suitable**
Castilla y León				
PAL-001	1,41	2,82	2,52	**Not Suitable**
PAL-002	1,43	2,73	2,93	**Not Suitable**
PAL-003	1,43	3,00	2,84	**Not Suitable**
SEG-001	2,70	2,81	2,66	**Suitable**
Catalonia				
BAR-002	3,00	2,80	2,70	**Suitable**
GER-001	3,00	2,93	2,71	**Suitable**
GER-002	3,00	2,75	2,70	**Suitable**
Madrid				
MAD-001	2,44	2,78	2,63	**Suitable**
MAD-002	2,45	2,70	2,55	**Suitable**
MAD-003	2,45	2,68	2,34	**Not Suitable**
MAD-004	2,45	2,68	2,34	**Not Suitable**
MAD-005	2,45	2,62	2,31	**Not Suitable**
MAD-006	2,45	2,91	3,00	**Suitable**
MAD-007	2,45	2,68	2,79	**Suitable**
MAD-008	2,44	2,81	2,39	**Not Suitable**
MAD-009	2,52	2,70	3,00	**Suitable**
C. Valenciana				
ALI-001	3,00	3,00	3,00	**Suitable**

Figure 11. Results of the first CFS assessment level for all case studies. Source: Preparation by the authors.

The possibility offered to establish an accessible tool for this decision-making, allows that products with a more environmentally sustainable and friendly consideration are brought to the market, which also provide a variety to normal solutions for the construction of non-load bearing enclosure walls. This strategy could be implemented in the rest of the constructive solutions and for the rest of the products that are being generated with environmentally friendly criteria, that can imply elements not trusted by building technicians.

In particular, from the CFS results in the 28 case studies, the following can be highlighted:

- EB quality, considering the categories established for the indicators, closely conditions the constructive feasibility of an architectonic solution. The results show that, when the EB does not have certified/declared durability requirements (in terms of resistance to dry/wet cycles, erosion, freeze/thaw cycles or capillary water absorption), and is exposed to unfavorable conditions, the *GI* indicate that the design must be revised for the suitable constructive layout.
- The values established for the weights and combinations are valid for a broad geographical context, on having been designed by international experts, although they could be adapted for other situations that were not considered.
- On analyzing the three categories of indicators set out, it can be highlighted that the constructive requirements provide the highest proportion of decisive indicators for the design of the wall's stable structure.
- Starting from the indicators used, it is confirmed that, as in any factory design, the start at the base or at its join with the foundation, the finishing of the outside wall and the design of openings are the singular points where the most decision

weights are accumulated and, therefore, are aspects to look out for to obtain the best degree of suitability.

In brief, it is concluded that this CFS can be used as a basic resource to make decisions in projects of new works or building retrofits where one wishes to use EB. To develop a set of criteria with greater applicability, economic, environmental or social indicators must be considered, which could be included in a methodological procedure that complements the one presented here.

ACKNOWLEDGEMENTS

First of all, we would like to thank Daniel Maskell, Guillermo Rolón, Miguel Rocha, Rubén Salvador Roux Gutiérrez and Félix Jové for their invaluable interest to provide their critical and technical views. Likewise, we thank all the technical staff, constructors, companies and private parties, especially the architect Gabriel Barbeta, for providing crucial information about all the domestic cases that made the development of this tool possible.

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Revista Hábitat Sustentable Vol. 10, N°. 2. ISSN 0719 - 0700 / Págs. 70 - 81
https://doi.org/10.22320/07190700.2020.10.02.05

Recibido 31/08/2020
Aceptado 12/12/2020

COMPRESSED EARTH BLOCKS (CEB) STABILIZED WITH LIME AND CEMENT. EVALUATION OF BOTH THEIR ENVIRONMENTAL IMPACT AND COMPRESSIVE STRENGTH

BLOQUES DE TIERRA COMPRIMIDA (BTC) ESTABILIZADOS CON CAL Y CEMENTO. EVALUACIÓN DE SU IMPACTO AMBIENTAL Y SU RESISTENCIA A COMPRESIÓN

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RESUMEN

En este trabajo se presenta la evaluación del impacto ambiental y la resistencia a compresión de Bloques de Tierra Comprimida (BTC) estabilizados con cal aérea hidratada y cemento Portland. Para esa labor, se fabricaron 12 series de bloques estabilizados con diferentes proporciones de cal y cemento y se empleó la metodología del Análisis de Ciclo de Vida (ACV). Tras la realización de los ensayos y las simulaciones pudo concluirse que, usando suelos y arena característicos de la ciudad de Santa Fe (Argentina), estabilizados con determinados porcentajes de cemento Portland -comprendidos entre el 5 y el 10% en peso- pueden producirse BTC con niveles de resistencia suficientes para ser utilizados en muros de carga y, de esa forma, minimizar el impacto ambiental negativo asociado a su fabricación. Se concluye, además, que la estabilización con cal aérea no incrementa la resistencia a compresión de los BTC y aumenta, por el contrario, de manera significativa el impacto negativo de éstos sobre el medio ambiente.

Palabras clave
tierra, estabilización, resistencia de materiales, impacto ambiental

ABSTRACT

This work presents the evaluation of the environmental impact and compressive strength of Compressed Earth Blocks (CEB) stabilized with hydrated aerial lime and Portland cement. For this, 12 series of blocks stabilized with different proportions of lime and cement were manufactured and the Life Cycle Analysis (LCA) methodology was used. After conducting these assays and simulations, it could be concluded that, using earth and sand typical of the city of Santa Fe (Argentina), stabilized with certain percentages of Portland cement between 5 and 10% in weight, CEB can be produced with sufficient levels of strength for them to be used in load-bearing walls, in this way minimizing the negative environmental impact associated with their manufacturing. It is also concluded that the stabilization with aerial lime does not increase the CEB's compressive strength and, on the contrary, significantly increases their negative impact on the environment.

Keywords
earth, stabilization, material strength, environmental impact

Revista Hábitat Sustentable Vol. 10, N°. 2. ISSN 0719 - 0700 / Págs. 70 - 81
https://doi.org/10.22320/07190700.2020.10.02.05

INTRODUCTION

Compressed Earth Block or CEB is masonry manufactured using the compression or pressing of stabilized soil inside a mechanical or hydraulic press (Neves & Borges Farías, 2011). These presses may be manual, for low production demands, or automatic, for industrialized systems (González & Cabrera, 2017). CEB technology started its development in Colombia at the beginning of the 1950s, together with the Inter-American Housing and Planning Center (CINVA), as an economic alternative of construction elements that is currently considered one of the most widespread Latin American technologies in the world (Angulo & Carreño, 2017).

CEB masonry is, in fact, an economic construction technique that has better strength and durability properties than those built with adobe, and a great potential for the industrialization of its units (Herrera Villa, 2018). In addition, these blocks have several advantages that allow them to face current energy and climate issues, on being elements manufactured with low energy materials (Bradley, Gohnert & Bulovic, 2018), compared to cooked clay bricks and sand-cement, in a way that they reduce the total energy required for construction and transportation, which is mainly due to the fact that earth is an abundant and recyclable natural resource (Ben Mansour, Ogam, Jelidi, Cherif & Ben Jabrallah, 2017; Hegyi, Dico & Catalan, 2016).

Just as with the rest of earth construction techniques, CEB have two main limitations:

- If the characteristics of the earth used for their manufacturing are not suitable, their compressive strength will not be enough to comply with structural functions (Ouedraogo, Aubert, Tribout & Escadeilas, 2020);
- Regardless of the type of earth used for their manufacturing, they show some durability issues: they degrade when facing certain atmospheric phenomena, especially water (Laborel-Préneron, Aubert, Jean-Emmanuel Magniont, Maillard & Poirier, 2016).

Both limitations can be minimized and, even, eliminated using small percentages of chemical stabilizers during their manufacturing which improve their physical-mechanical properties, increasing their strength and durability (Guzmán & Iñiguez, 2016).

Different additives have been used in the stabilization of the CEB: from natural substances like aloe vera (Aranda Jiménez & Suárez-Domínguez, 2014), casein and cellulose (Vissac, Bourges & Gandreau, 2017), to oil byproducts like natural bitumen and asphaltic emulsions (Van Damme & Houben, 2018). However, since the origins of this technology, the most used stabilizer has been Portland cement (Elahi, Shahriar, Alam & Abedin, 2020), which is the case in numerous regions of Argentina and Latin America where they are known as "Cement Earth Blocks", a lexicon that is greatly influenced by highway engineering.

Despite the good performance that CEB stabilized with cement have, it must be considered that, together with the high economic cost of this additive, their manufacturing also requires high thermal transformation processes, reaching 1,450°C, ones that release enormous amounts of CO_2 into the atmosphere. It is estimated that for each ton of Portland cement produced, 0.86 tons of CO_2 are released into the atmosphere (Guilarducci, 2018).

Another frequently used additive in the stabilization of CEB is lime, both aerial and hydraulic (Malkanthi, Balthazaar & Perera, 2020), whose environmental impact is significantly lower than Portland cement for the following reasons:

- The temperature required for its manufacturing is approximately 900°C (Maddalena, Roberts & Hamilton, 2018);
- It can be produced on a small scale and on an artisanal level (Guapi Cepeda & Yagual Flores, 2017);
- Aerial lime has the property of absorbing, during its hardening process (carbonation), a large part of the CO_2 released into the atmosphere during its manufacturing process (Qiu, 2020).

Many countries have specific technical standards for construction with earth; however, there are few that have specific testing standards for CEB published by Official Standardization Entities, among which Brazil, Colombia, France, Spain and Mexico stand out (Cabrera, González & Rotondaro, 2020).

In this context, the general objective of this research consisted in evaluating the mechanical and environmental properties of the CEB stabilized with hydrated aerial lime and contrast them with their equivalents stabilized with Portland cement. For this, the following particular objectives are proposed:

- Determining the average compressive strength of CEB stabilized with different percentages of hydrated aerial lime and Portland cement;
- Correlating the average compressive strength of CEB with the percentage and type of stabilizer used.
- Calculating the environmental impact of the CEB stabilized with different proportions of lime and cement.

Revista Hábitat Sustentable Vol. 10, N°. 2. ISSN 0719 - 0700 / Págs. 70 - 81
https://doi.org/10.22320/07190700.2020.10.02.05

Sieve		4.75 mm	0.425 mm	0.250 mm	0.150 mm	0.075 mm	0.002 mm
Undersize (%)	Earth	0.0	86.0	-	-	57.0	29.0
	Sand	100	96.2	89.3	48.7	0.6	0.0

Tabla 1. Granulometría de la materia prima. Fuente: Elaboración de los autores.

METHODOLOGY

CEB MANUFACTURING

The earth used in the manufacturing of CEB came from a quarry located in the commune of Monte Vera (Santa Fe, Argentina) classified as a low plasticity clay marl "CL-ML" with 29% clay (kaolinite and illite) and a linear contraction index of 4%. With the intention of improving the granulometric curve of earth and thus increase the compressive strength of the CEB produced (Sitton, Zeinali, Heidarian & Story, 2018), it was mixed with sand from the Paraná river, which is mainly quartz (SiO_2). The granulometric distribution of the earth and sand used in the manufacturing of the CEB can be seen in Table 1.

To determine the compressive strength of CEB stabilized with different proportions of lime and cement, 12 series of 5 CEB each were manufactured in a laboratory, keeping the earth/sand ratio fixed. Blocks of 25.0 x 12.5 x 6.25 cm were produced with two vertical 6.0 cm diameter holes, using an Eco Brava hydraulic press for this purpose, developed by the Brazilian company, "Eco Máquinas". All the series were made with 12.5% moisture, considering the dry weight of the materials. The stabilizers used were hydrated aerial lime from the "Andina" brand and CPC-40 compound Portland cement made by "Holcim". Finally, the different doses used are expressed in Table 2.

The CEB produced were cut in half, thus generating 2 CEB specimens of 12.5 x 12.5 x 6.5 cm, from which, 6 per series were chosen randomly to subject them to the compressive strength test stipulated by the Mexican standard NMX-C-508 (ONNCCE, 2015): test without heading and variable load speed (for which the test lasts between 1 and 2 minutes). All the specimens were tested dry with 28 days of age and cured for 7 days (with the exception of the series without stabilizer) at a relative humidity of 100%, then remaining for 21 days in a laboratory environment, at a relative humidity of 55% and at 24°C.

Serie		Earth (%)	Sand (%)	Lime (%)	Cement (%)
Cement	Cmt. 0%	50.0	50.0	-	0.0
	Cmt. 2.5%	48.75	48.75	-	2.5
	Cmt. 5%	47.5	47.5	-	5.0
	Cmt. 10%	45.0	45.0	-	10.0
	Cmt. 15%	42.5	42.5	-	15.0
	Cmt. 20%	40.0	40.0	-	20.0
Lime	Lime 0%	70.0	30.0	0.0	-
	Lime 2.5%	68.25	29.25	2.5	-
	Lime 5%	66.5	28.5	5.0	-
	Lime 10%	63.0	27.0	10.0	-
	Lime 15%	59.5	25.5	15.0	-
	Lime 20%	56.0	24.0	20.0	-

Table 2. Dosage in weight of the different CEB series. Source: Preparation by the authors.

In order to evaluate the results obtained and determine whether the average compressive strengths of each series were statistically different to each other, an ANOVA variance analysis and a "Tukey pairs analysis" were made, using the Mini Tab[1] statistical software.

LIFE CYCLE ANALYSIS

To determine the environmental impact of CEB stabilized with different lime and cement contents, the Life Cycle Analysis (LCA) methodology, proposed by the IRAM-ISO 14040 standard (IRAM, 2017) was used. This allows characterizing and quantifying different potential environmental impacts associated to each one of the stages of the lifespan of a product or system (Carretero-Ayuso & García-Sanz-Calcedo, 2018). To perform the inventory analysis proposed by IRAM-ISO 14040, the SimaPro9 software (Copyright Pré, 2019) was used.

1 Minitab Statistical Software. See: https://www.minitab.com/es-mx/company/

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UNIT OF ANALYSIS

In this framework, individual CEB of 15 x 30 x 7.5 cm were adopted as functional units, with two 6 cm diameter holes (geometry of the CEB produced by Mobak, in Santa Fe, Argentina) and a mass of 4 kg, each one with a different lime or cement content, matching the dose of the blocks tested for compression (see Table 2).

LIMITS OF THE SYSTEM

The scope of the study was limited to the approach called "from the cradle to the gate", through which only the entry and exit flows of the stages between the extraction of the raw materials needed for the manufacturing of the blocks, until these are finished and ready to be inserted in the market, outside the production plant (Curadelli, López, Piastrellini, Arena & Civit, 2019) are considered. To quantify the impact associated to the transportation of the raw materials from their extraction or acquisition site, the following was considered:

- Production unit: The analysis model was based on the Mobak CEB Factory, located in the commune of Arroyo Leyes (Santa Fe), whose production capacity is 3,000 CEB per day.
- Earth: The earth extraction quarry is located in the commune of Monte Vera (Santa Fe), 35 km from the factory.
- Sand: The acquisition of the sand used in the manufacturing of the blocks took place in a sand pit in the city of Santa Fe, 19km from the production unit.
- Stabilizers: The use of hydrated aerial lime in 25 kg bags and Portland cement in 50 kg bags was considered. Both were bought at a yard located to the north of Santa Fe, 35 km from the factory.
- Transportation: The use of a euro3 type truck with 16-32 tn capacity was considered for the transportation of the earth and sand; while, for the stabilizers, a euro3 truck with 7.5-16 tn capacity was used. These vehicle categories were adopted following the requirements stipulated by the European Union's N5 Standard (EU, 2007).
- Raw material production and extraction: with the objective of quantifying the impact associated to the extraction and sale of earth and sand, and the production of lime and cement with their corresponding distribution to the sales centers, the Ecoinvent3 database found in the SimaPro software (Copyright Pré, 2019) was used.

FIELDWORK

For the sake of quantifying the consumption of energy and resources and the residual outtake corresponding to the manufacturing stage of this type of blocks, field visits were made to the CEB production company, "Mobak"[2], where the data required was recorded onsite.

In every visit that was made, notes were taken on the amount, proportion and origin of the raw materials used to produce the CEB, as well as the final destination of the already manufactured product, with the purpose of determining the transportation distances. The production process was documented, specifying the stages, machinery and type of energy used in each phase of the process. In addition, the name, brand, and model of the machinery used was recorded, along with its production capacity and the energy efficiency of each operation expressed in energy units. Likewise, the different means of transportation used were recorded, as well as their load capacity and the distances covered.

Figure 1 summarizes the production process applied by Mobak in the manufacturing of their CEB, where, unlike the dosages proposed for this research, two types of sand with different granulometries are added, and both lime and cement are added for the stabilization.

RESULTS

COMPRESSIVE STRENGTH

Table 3 details the results of the compressive strength tests made on each one of the series of specimens: number of specimens tested (N), average compressive strength (μ) and standard deviation (σ) of each series, the value of the statistics P, resulting from the variance analysis and the group factors of the Tukey pairs analysis. Figure 2 shows the average compressive strengths of each CEB series produced.

2 CEB factory located in the commune of Arroyo Leyes, Province of Santa Fe (Argentina).

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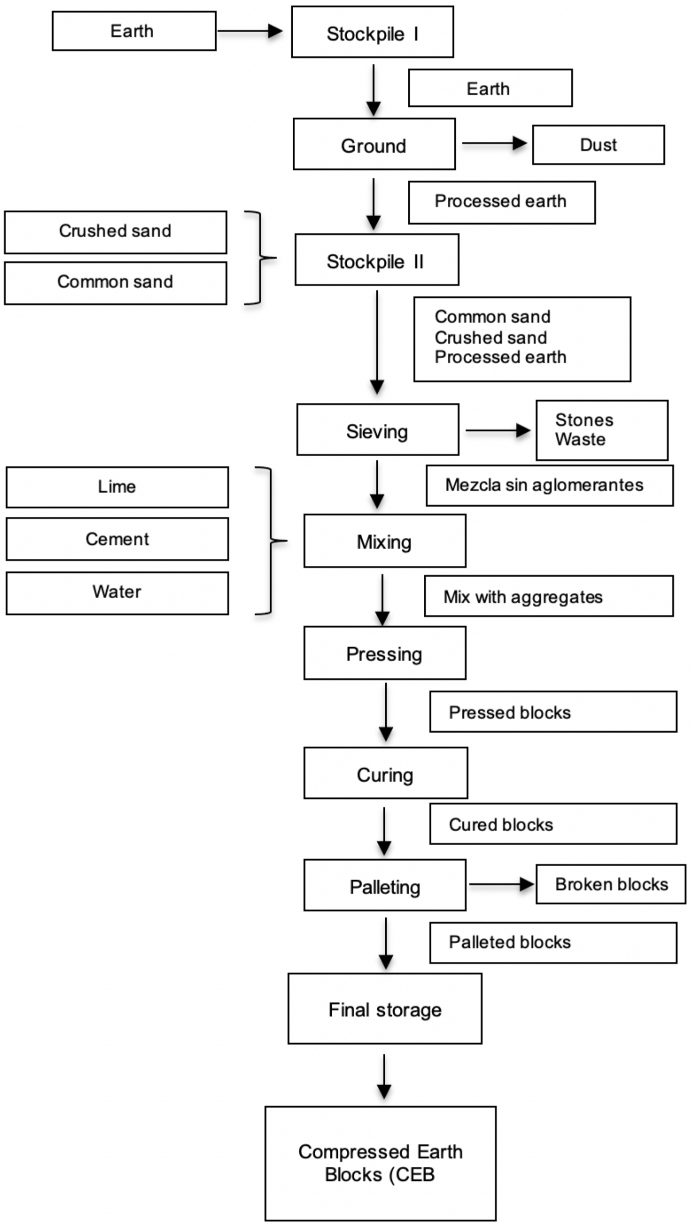

Figure 1. CEB production flow chart. Source: Preparation by the Authors.

Series		N	μ (MPa)	σ (MPa) p	ANOVA	
					Group	
Cement	Cmt 0%	6	0.76	0.26	< 0.001	A
	Cmt 2.5%	6	0.81	0.14		A
	Cmt 5%	6	1.39	0.16		A
	Cmt 10%	6	5.09	0.52		B
	Cmt 15%	6	6.08	0.77		B
	Cmt 20%	6	7.426	1.34		C
Lime	Lime 0%	6	0.57	0.13	0.372	D
	Lime 2.5%	6	0.57	0.08		D
	Lime 5%	6	0.57	0.03		D
	Lime 10%	6	0.66	0.12		D
	Lime 15%	6	0.60	0.10		D
	Lime 20%	6	0.54	0.05		D

Table 3. Descriptive statistics, ANOVA variance analysis and grouping as per the Tukey analysis of the CEB series. Source: Preparation by the authors.

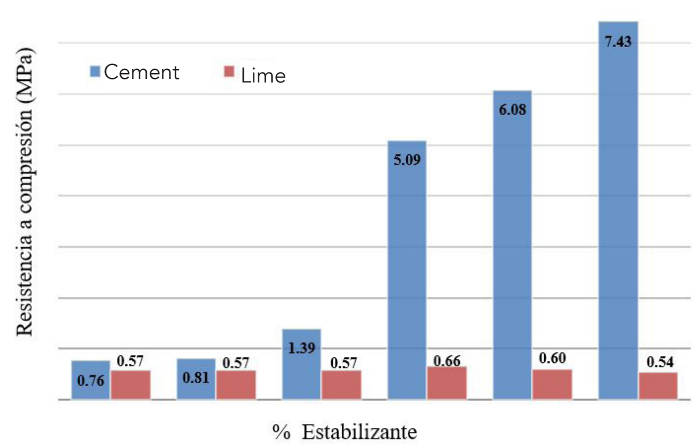

Figure 2. Compressive strength of the different CEB series. Source: Preparation by the authors.

FIELDWORK

In Table 4, the energy consumption associated to each stage of the CEB production process is seen. These consumptions were obtained after surveying Mobak's production plant: an average production of 36 batches per day, each one of these with 55 CEB. The assigning of the energy consumption per base unit (1 CEB) was made by dividing the electricity consumption of the entire batch by 55.

Energy consumption per operation	Equipment's power (KW)	Use time per batch (min)	Energy consumed per batch (MJ)	Energy consumed per CEB (KJ)
Clod crusher	2.0	8.5	1.020	0.0185
Sieving machine	1.1	8.5	0.561	0.0102
Mixer	5.5	7.0	2.310	0.0420
Short conveyor belt	0.8	7.0	0.336	0.0061
Long conveyor belt	1.1	7.0	0.462	0.0084
Hydraulic press	3.0	8.5	1.530	0.0278
Curing	0.4	-	-	0.0024
			TOTAL	0.1155

Table 4. Energy consumed in each stage of the manufacturing process of 1 CEB. Source: Preparation by the Authors.

Serie	Acidification of the soil and water	Eutrophication of the water	Global warming	Photochemical oxidation	Mineral consumption	Fossil fuel consumption	Water consumption	Ozone layer deterioration
	(kg SO2 eq)	(kg PO4 eq)	(kg CO2 eq)	(kg NMVOC)	(kg Sb eq)	(MJ)	(m3 eq)	(kg CFC-11 eq)
Lime 0%	2.270E-04	4.733E-05	0.0419	2.427E-04	1.110E-07	0.6137	0.1085	5.761E-09
Lime 2.5%	3.530E-04	6.798E-05	0.1350	3.624E-04	1.242E-07	1.0708	0.1104	1.130E-08
Lime 5%	4.790E-04	8.864E-05	0.2280	4.821E-04	1.374E-07	1.5278	0.1123	1.685E-08
Lime 10%	7.311E-04	1.299E-04	0.4150	7.216E-04	1.639E-07	2.4419	0.1161	2.793E-08
Lime 15%	9.831E-04	1.713E-04	0.6010	9.610E-04	1.903E-07	3.3559	0.1198	3.902E-08
Lime 20%	1.235E-03	2,126E-04	0.7870	1.200E-03	2.167E-07	4.2700	0.1236	5.010E-08
Cmt 0%	2.489E-04	5.420E-05	0.0453	2.650E-04	1.296E-07	0.6532	0.1579	6.063E-09
Cmt 2.5%	4.515E-04	1.019E-04	0.1380	4.443E-04	1.701E-07	1.0228	0.1609	8.701E-09
Cmt 5%	6.541E-04	1.497E-04	0.2310	6.237E-04	2.105E-07	1.3924	0.1639	1.134E-08
Cmt 10%	1.059E-03	2.451E-04	0.4160	9.825E-04	2.913E-07	2.1316	0.1699	1.661E-08
Cmt 15%	1.038E-03	3.462E-04	0.4920	1.017E-03	2.575E-07	1.6293	0.1569	1.361E-08
Cmt 20%	1.870E-03	4.360E-04	0.7870	1.700E-03	4.530E-07	3.6100	0.1820	2.717E-08

Table 5. Results of the impact inventory of the different CEB series.Source: Preparation by the Authors.

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ENVIRONMENTAL IMPACT

When it comes to expressing the results of the life cycle analysis made on the 12 series of CEB using the Simapro software, the EPD 2018 (Environmental Product Declarations) method was used, which quantifies the environmental impact in 8 impact levels, which can be seen in Table 5.

DISCUSSION

COMPRESSIVE STRENGTH

The effect of the stabilizer content on the compressive strength of the different CEB series presented different behaviors depending on the type of additive used. It can be considered, with 95% confidence, that the mean compressive strength of all the series stabilized with lime, regardless of the percentage used, is statistically equal to the mean compressive strength of the CEB series without being stabilized.

On the other hand, the strength of the CEB with cement was seen to be greatly affected by the percentage of stabilizer used: the series of blocks stabilized with 2.5 and 5% of cement presented, from a statistical point of view, a mean compressive strength without a significant difference between them, and equal to that of CEB without any stabilizer (group factor A). The blocks with 10 and 15% of cement had statistically even strengths and greater than those of their homolog with low cement contents (group factor B), while the series stabilized with 20% cement had a mean compressive strength that was greater than the rest of the series (group factor C). The ratio between the lime and cement content used for the stabilization and the mean compressive strength of the CEB can be seen in Figure 3.

The results obtained match those of previous research made by the Geotechnical Laboratory of the National Technological University, Regional Faculty of Santa Fe (UTN-FRSF), where it has been shown that the compressive strength of the CEB stabilized with lime is significantly lower than those of its homologs stabilized with an equal proportion of cement (Cabrera, González & Rotondaro, 2019), which likewise coincides and reinforces the results generated by different researchers (González-López, Juárez Alvarado, Ayub Francis & Mendoza Rangel, 2018; Laguna, 2011), Ouedraogo et al., 2020).

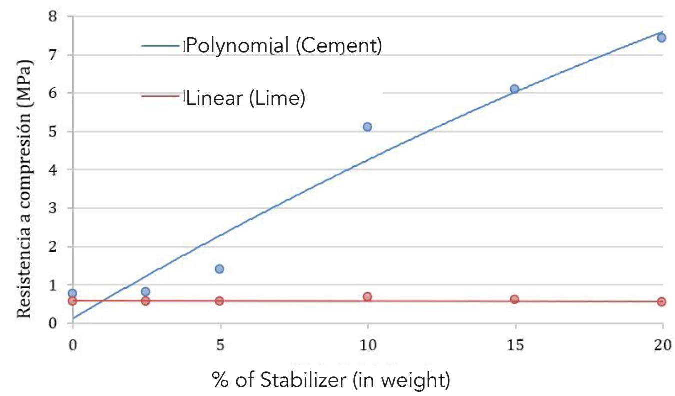

Figure 3. Interpolation curves of compressive strength vs. percentage of lime or cement used in the stabilization of the CEB. Source: Preparation by the Authors.

ENVIRONMENTAL IMPACT

Figure 4 graphically expresses the results from Table 5 and those obtained after making the inventory analysis of the CEB being studied. Regarding the acidification of the soil and water (1), the eutrophication of water (2), the photochemical oxidation (4), and the mineral consumption (5), the impact factor increases with the stabilizer content, in all cases being higher for the CEB stabilized with cement. On the contrary, the fossil fuel consumption (6) and the ozone layer deterioration (8) are significantly higher for the CEB stabilized with lime than with cement, which does not happen with the emissions of CO_2 equivalent (3) which, despite significantly increasing with the content of the stabilizer used, remain practically alike for both stabilizers.

It is interesting to highlight how the water consumption (7) is higher in the CEB stabilized with cement than those stabilized with lime. However, as can be seen in the first quadrant of Figure 4, this is not due to the type of stabilizer used, but rather, to the higher content of sand used in the manufacturing of these blocks, since its extraction demands large volumes of water compared to those required for exploitation in an earth quarry.

The comparison between energies incorporated by different researchers is no easy task since, apart from the different raw materials and manufacturing processes analyzed, each piece of research has different objectives, scopes and inventories. In Table 6, the energy incorporated by the different series of CEB analyzed in this work can be seen in detail, between 0.65 and 4.27 MJ/CEB, depending on the

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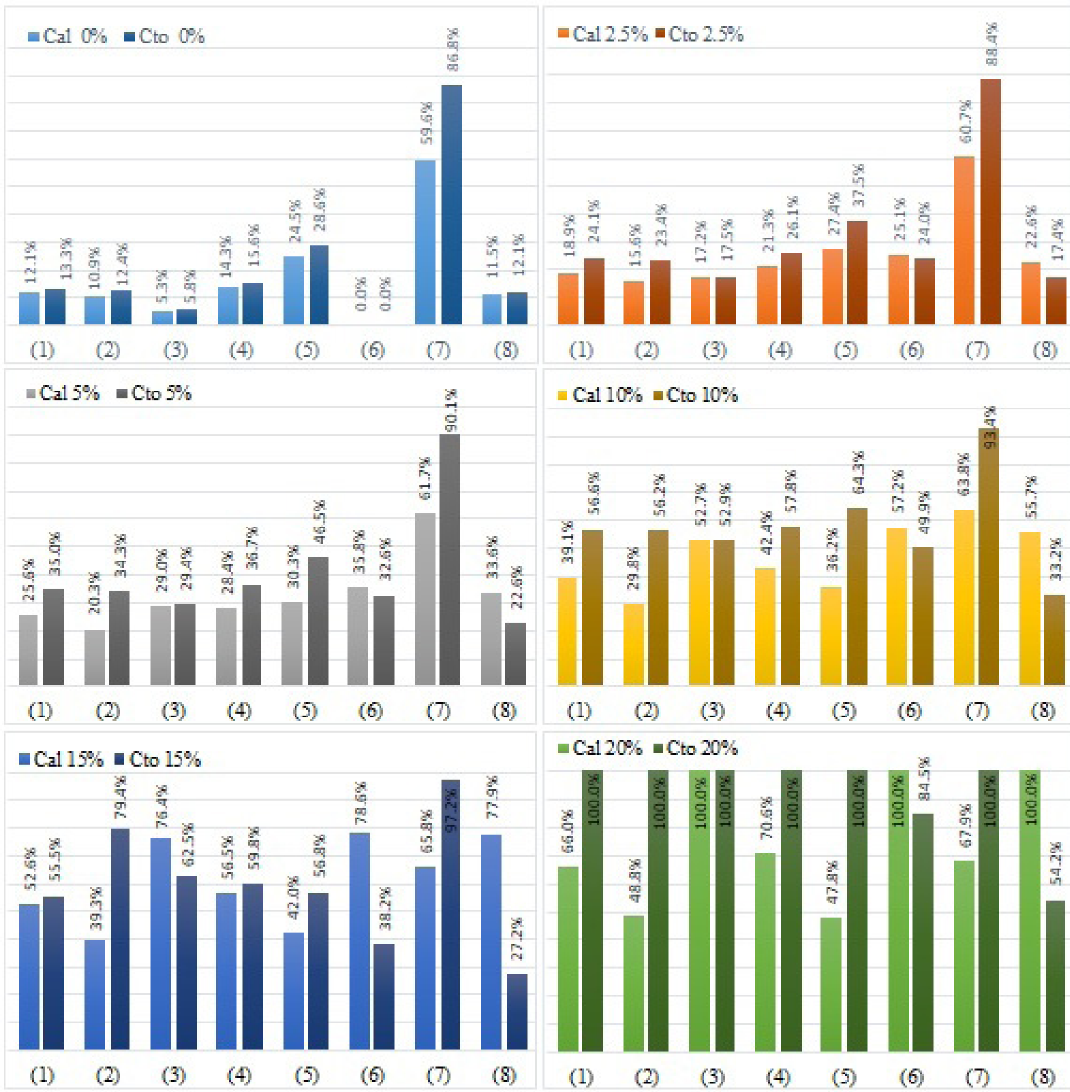

(1) Acidification of the soil and water
(2) Eutrophication of the water
(3) Global warming
(4) Photochemical oxidation
(5) Mineral consumption
(6) Fossil fuel consumption
(7) Water consumption
(8) Ozone layer deterioration

Figure 4. Comparison between the different impact factors of CEB stabilized with lime and cement in different proportions. Source: Preparation by the Authors.

Authors	Energy Incorporated (MJ/BTC)	Stabilizer used
Vázquez Espi, 2001	0.18 - 5.76	Different proportions of Portland cement
Roux Gutiérrez & Espuna Mujica, 2016	7.62	7% of hydrated aerial lime
Fernandes, Peixoto, Mateus & Gervásio, 2019the life cycle assessment of building materials is still in its infancy. So far, there is only a small number of Environmental Product Declarations (EPDs	3.94	6.5% of hydraulic lime
This research	0.65 – 4.27	Different proportions of lime and Portland cement.

Table 6. Energy incorporated during the manufacturing of a CEB published by different authors.Source: Preparation by the Authors.

amount and type of stabilizer used, and depending on the results published by the different authors, whose similarity is left clear.

CONCLUSIONS

After evaluating the results of the compressive strength tests of the different series of CEB manufactured at the Geotechnical Laboratory of UTN-FRSF and the environmental impact associated to their production, it is possible to make the following conclusions:

- The incorporation of hydrated aerial lime in the stabilization of the CEB does not improve their simple compressive strength.
- The stabilization with Portland cement significantly increases the compressive strength of the blocks, noting a considerable improvement for percentages over 5% in weight.
- The stabilization of CEB with lime or cement, even in small amounts, has the greatest responsibility for the negative environmental impact of these blocks.
- The replacement of lime by cement in the stabilization of the CEB does not significantly reduce the environmental impact associated to its production.

Finally, it can be confirmed that, using earth and sand typical of the city of Santa Fe (Argentina), stabilized between 5% and 10% in weight by Portland cement, sufficient compressive strength levels are reached for structural purposes, and the environmental impact associated to this type of masonry is minimized. It is also concluded that the stabilization with lime does not increase the compressive strength of the CEB or significantly increase the negative impact of these on the environment.

To continue with this research, the plan is to make Life Cycle Analyses of other masonry of the region, like the concrete block or the ceramic brick, comparing their environmental impact with that of the CEB stabilized with 5 and 10% cement, and their economic impact on construction. Likewise, the effect of the stabilization with hydrated aerial lime on the compressive strength in the long term and the durability of the CEB could be studied.

ACKNOWLEDGEMENTS

This work falls within the Research and Development Project called "Analysis of the properties of Compressed Earth Blocks (CEB), stabilized with lime" (MSUTIFE0004877TC), financed by the National Technological University (Argentina). We would also like to thank the National Council on Science and Technology (CONACYT Mexico), and the National Scientific and Technical Research Council (CONICET) for financing the work of the authors, and to the company, "Mobak", for their contributions.

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Revista Hábitat Sustentable Vol. 10, N°. 2. ISSN 0719 - 0700 / Págs. 82 - 93
https://doi.org/10.22320/07190700.2020.10.02.06

Recibido 16/06/2020
Aceptado 27/10/2020

THERMAL PERFORMANCE OF TRADITIONAL EAST FACING GREEN FACADES IN TRACT HOUSING LOCATED IN ARID CLIMATES

DESEMPEÑO TÉRMICO DE FACHADAS VERDES TRADICIONALES DE ORIENTACIÓN ESTE EN VIVIENDAS SERIADAS EMPLAZADAS EN CLIMAS ÁRIDOS

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RESUMEN

La infraestructura verde constituye una estrategia de mitigación de las temperaturas urbanas y edilicias. El presente trabajo evalúa el impacto de un tipo de Sistema de Enverdecimiento Vertical (SEV), las Fachadas Verdes Tradicionales (FVT), en la condición térmica de viviendas localizadas en el Área Metropolitana de Mendoza, Argentina; cuyo clima es seco desértico (BWk - Köppen-Geiger). Con tal fin, se monitorearon, durante dos veranos consecutivos, dos casos de estudio: una vivienda con FVT, en orientación este, y una vivienda testigo de igual tipología y materialidad. Se registraron datos de temperatura ambiente exterior e interior; superficial exterior e interior y radiación horizontal. Se hallaron disminuciones de hasta 3.1°C en la temperatura ambiente interior de las viviendas con FVT, de hasta 27.4°C en muros exteriores y de 6.5°C en muros interiores. Las magnitudes de los resultados encontrados demuestran el potencial de la aplicación de esta estrategia en un clima árido.

Palabras clave
zonas áridas, arquitectura bioclimática, viviendas unifamiliares, Sistemas de Enverdecimiento Vertical.

ABSTRACT

Green infrastructure is a strategy for mitigating urban and building temperatures. This work assesses the impact of a type of Vertical Greenery System (VGS), the Traditional Green Façades (TGF), on the thermal condition of dwellings located in the Metropolitan Area of Mendoza, Argentina, whose climate is dry desert (BWk - Köppen-Geiger). To this end, two case studies were monitored for two consecutive summers: a dwelling with an east-facing TGF and a control dwelling of the same typology and materiality. Outdoor and indoor ambient temperature data were recorded: surface exterior and interior, and horizontal radiation. Decreases of up to 3.1°C in the indoor ambient temperature of FVT dwellings, of up to 27.4°C on exterior walls and 6.5°C on interior walls were found. The magnitudes of the results found show the potential of applying this strategy in an arid climate.

Keywords
arid zones, bioclimatic architecture, single dwellings, Vertical Greenery Systems

INTRODUCTION

In densely populated areas, there are negative impacts typical of the advance of urbanity on the environment, from carbon emissions and the increase of average air temperatures, to the laying waste of periphery production areas and the destruction of ecosystems. According to data from the International Energy Agency (OECD / IEA, 2017), cities cover 3% of the planet's surface and, apart from causing the increase in the average air temperature, they are responsible for 67% of global energy consumption. At the same time, the United Nations Environment Program (UNEP) indicates that 75% of the infrastructure there will be in 2030, has not yet been built. This represents an opportunity to create "clean and green cities", that are efficient and resilient. One strategy to reach this goal is urban greenery.

Green infrastructure generates environmental-energy benefits: at an urban scale, it reduces the heat island and increases the comfort of public spaces and, at a building scale, it reduces energy consumption to condition indoor spaces. Recent research has determined that in a template climate, a 10% increase of green infrastructure could reduce average urban air temperatures by 2.5°C (Gill, Handley, Ennos & Pauleit, 2007) and, that in a dry arid climate, the ambient temperature in a tree covered area could fall 3.8°C (Salas & Herrera, 2017). In addition, green spaces generate benefits for peoples' health and welfare (Contesse, Van Vliet & Lenhart, 2018). Given that the city consolidation phenomenon has held back the potential of incorporating traditional green structures like parks, squares and tree-lined streets, new vegetation typologies associated to green walls and roofs have emerged.

The development of knowledge linked to Vertical Greenery Systems (VGS) has grown in terms of its international relevance in the last decade (Bustami, Belusko & Beecham, 2018). They show proven efficiency in reducing temperatures of living spaces and their resulting impact on energy consumption. The results vary in their magnitude, depending on the type of climate where VGS are applied, recording the highest outdoor surface temperature reductions of around 34°C (Suklje, Saso & Arkar, 2016) in Cfa/Cfb type climates (humid warm template, hot summer) and indoor room temperature of around 5°C (Haggag, Hassan & Elmasry, 2014) in BWh type climates (desert arid, hot summer) and outdoor ambient temperature of around 3.3°C (Wong, Kwang Tan, Tan, Chiang & Wong, 2010) in AF type climates (Humid equatorial). Most of the studies have been run in European, Asian and North American countries, in warm template, both humid and dry – Csa, Cfa/Cfb - climates. The results have shown similar or better performance for VGS, regarding temperature reductions, in arid climates compared to humid ones.

The Metropolitan Area of Mendoza, Argentina (AMM, in Spanish), has a desert arid climate (BWk - Köppen-Geiger). From the point of view of the presence of vegetated spaces, it has a relevant number of forested open spaces within its structure. However, the urban densification and growth process has not been accompanied by a densification process of the urban greenery and also, the availability of empty urban spaces that allow incorporating traditional green spaces has also been limited. As a result, increasing green areas implies implementing new vegetation technologies like VGS, among others.

The thermal-energy benefits of VGS are associated to diverse effects. First, the *shading effect*, which places the VGS as interceptors of direct or indirect incident solar radiation. This effect, depending on the wall's orientation, is important in climates with a strong solar incidence (Othman & Sahidin, 2016). Secondly, the *cooling effect* that reduces air temperature and increases humidity, releasing water vapor from plants into the atmosphere (Wong & Baldwin, 2016). It is proven that the reach of this extends up to 60 cm from its surface (Wong et al., 2010). The *insulation effect* also has to be mentioned. This is produced by the layers that the VGS construction package comprises, that interfere in the heat transmission of building envelopes. And finally, the *windbreak effect*, which causes reductions in heat losses or gains through convection due to the ruggedness of foliage that blocks air circulation. Regarding the impact of VGS on energy savings, Coma et al. (2017) have recorded values of around 58.9%. In terms of environmental benefits, carbon emissions absorption values were recorded that range between 0.14 and 0.99 kg/m^3 (Marchi, Pulselli R., Marchettini, Pulselli F & Bastianoni, 2015). This, apart from the impact it generates on the degree of noise absorption and the contribution to the preservation of biodiversity. Finally, green façades increase the perception of comfort, relaxation and improve people's moods (Elsadek, Liu & Lian, 2019).

VGS are grouped into two categories: Living Walls (LW) and Green Façades (GF) (Figure 1). GF are those systems where there are climbing and/or hanging plants, covering a given area. They can be divided into three typologies: Traditional Green

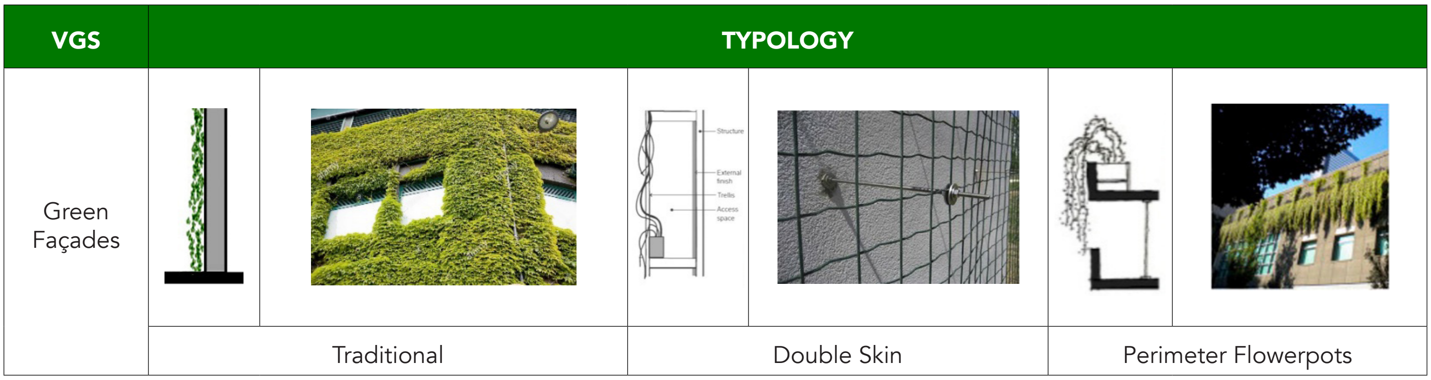

Figure 1. GF Typologies. Source: Preparation by the authors.

Façades (TGF), where the plant attaches itself to the building's wall; Double Skin Green Façades (DSGF) or green curtain wall, where there is a supplementary structure that is separated, at a variable distance, from the building's wall; and Green Façades with Perimeter Flowerpots (PFGF), which can house flowerpots with climbing and/or hanging plants to generate a green curtain wall.

TGF are systems whose application is simple, low-cost and have a reduced impact on the existing construction. In the case of Mendoza, this strategy is one of a spontaneous application that is widespread in residential low-density areas. The benefits are classified in two categories: thermal-energy and environmental.

The thermal-energy benefits have been extensively analyzed in international literature. However, the development of knowledge regarding the incidence of TGF on the thermal behavior of indoor spaces in desert type climates is limited, as is the analysis of the differential impact of using the strategy, considering the orientation of the façade.

In this context, Alexandri & Jones (2008) determine for the case of Athens, Greece, whose latitude (32° N) is comparable to that of Mendoza (37° S). that the maximum radiation received in summer on east- and west-facing vertical planes is 1.65 times greater than that received on north and south planes. Meanwhile, Susorova, Angulo, Bahrami & Stephens (2013), measure the effect of TGF on building walls in the four orientations in Chicago, finding greater magnitudes, around 4 to 5 times higher, for east and west orientations. Coma et al. (2017) determine that DSGF type facades are more effective on west and east sides than on the north one. Recent studies assign greater cooling and energy saving magnitudes produced by an east and west-facing GF in summer conditions (Pérez, Coma, Sol & Cabeza, 2017) (Kontoleon & Eumorfopoulou, 2010). From all this, it can be seen that VGS generate the greatest impact on east and west facing positions whose vertical planes are those most demanded by solar radiation.

As a result, the objective of this work is to evaluate the impact of east-facing TGF, on indoor and outdoor surface temperatures, and the thermal condition of indoor spaces in terraced single-family dwellings in AMM, Argentina.

WORK HYPOTHESIS

In arid climates, new vegetation technologies, in particular Traditional Green Façades, constitute a passive bioclimatic conditioning strategy due to their capacity to attenuate the surface temperatures of the building envelope, and to approach comfort conditions in the inhabitable spaces in the warm season.

METHODOLOGY

CASE STUDIES

To carry out this study, two dwellings were chosen, located in a terraced typology neighborhood in Guaymallén, Mendoza. The morphology of both houses is compact, extended and structured on two levels. Figure 2 shows the location of the dwellings in the context of the Mendoza Metropolitan Area (AMM). And, in Figure 3, the morphological type of the buildings is seen along with the hour-by-hour sunlight study of incident solar radiation on the east façade.

Technologically, the cases of analysis show a construction type, typical of seismic areas:

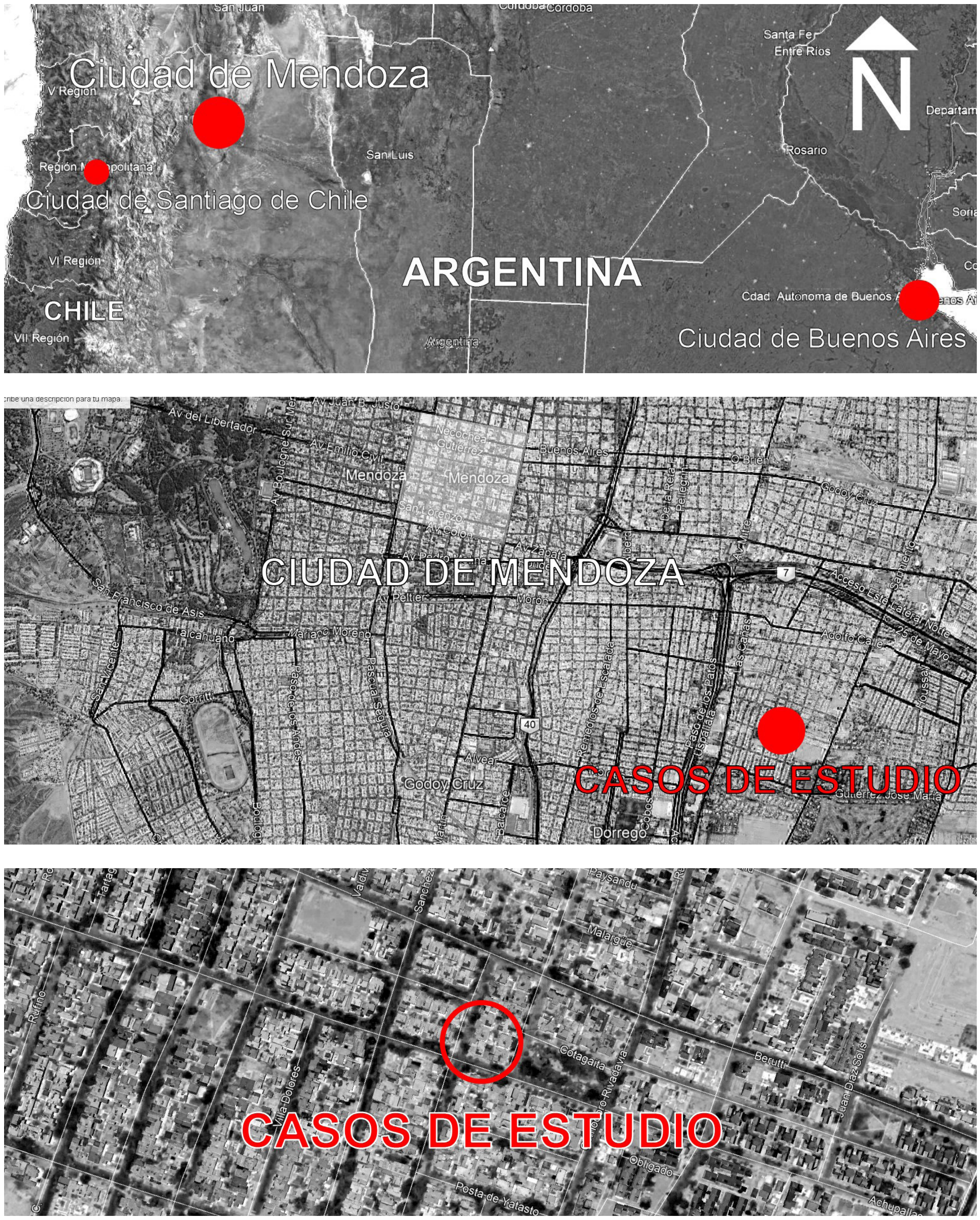

Figure 2: Location of the dwellings in the context of AMM. Source: Preparation by the Authors.

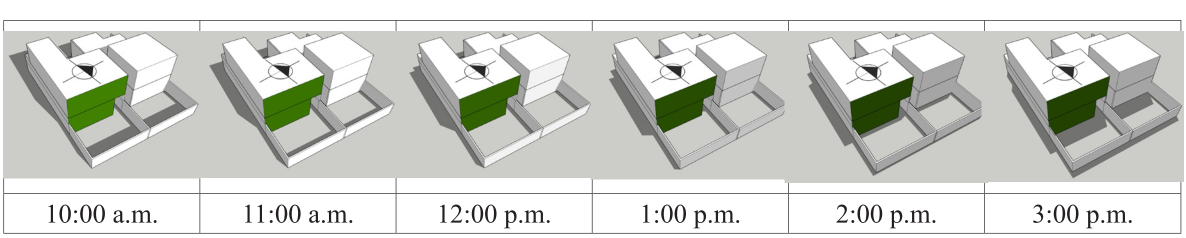

Figure 3. Hour by hour sunlight study of the incident solar radiation on the east façade. Source: Preparation by the Authors.

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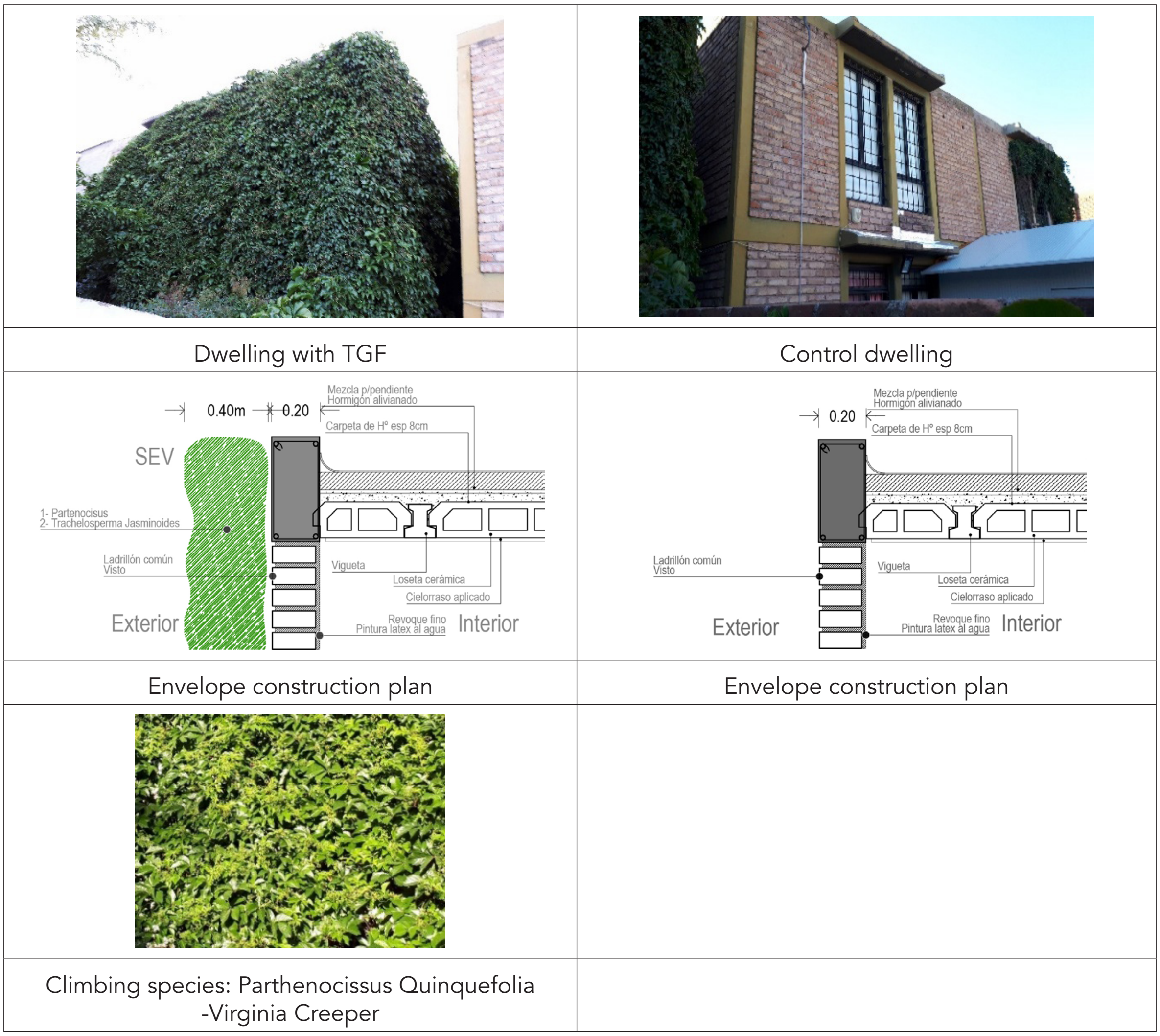

Figure 4. Case studies Source: Preparation by the authors.

reinforced concrete and visible brick masonry structure. The roofs are flat, formed by thermically and hydraulically insulated lightened concrete slabs. One of these has the TGF system on the internal east-facing façade of the dwelling and on the north-facing façade. The TGF is a simple system formed by a climbing plant of the Parthenocissus *Quinquefolia* species, from the Vitaceae family, locally known as the Virginia Creeper, a species originally from North and Central America; woody, deciduous, hardy, fast growing, high foliage density and adaptable (tolerates most soils and climate conditions), low solar permeability and upkeep, it is widely used in the region. It has grown attached to the wall with an average thickness of 40 cm over its whole extension and covers 100% of the masonry wall which forms the east façade of the dwelling (Figure 4).

CASE STUDY MONITORING

To evaluate the impact of TGF on the thermal behavior of the dwellings' east facing façades, the variables measured were the following: outdoor air humidity and temperature in the open public and private spaces next to the dwellings, indoor air humidity and temperature and indoor and outdoor surface temperature on walls. The sensors used to measure the environmental relative humidity and temperature were a thermistor and thermocouple type, HOBO Onset, UX100-003, UX120. The location of the sensors and equipment used is presented in Figure 5.

The data were recorded in two periods: summer 2019 – 21/01 to 05/02 and 2020 – 30/01 to 14/02, over 15 days, with data being recorded every 15 minutes. The sensors were calibrated beforehand to guarantee reliability of the data obtained.

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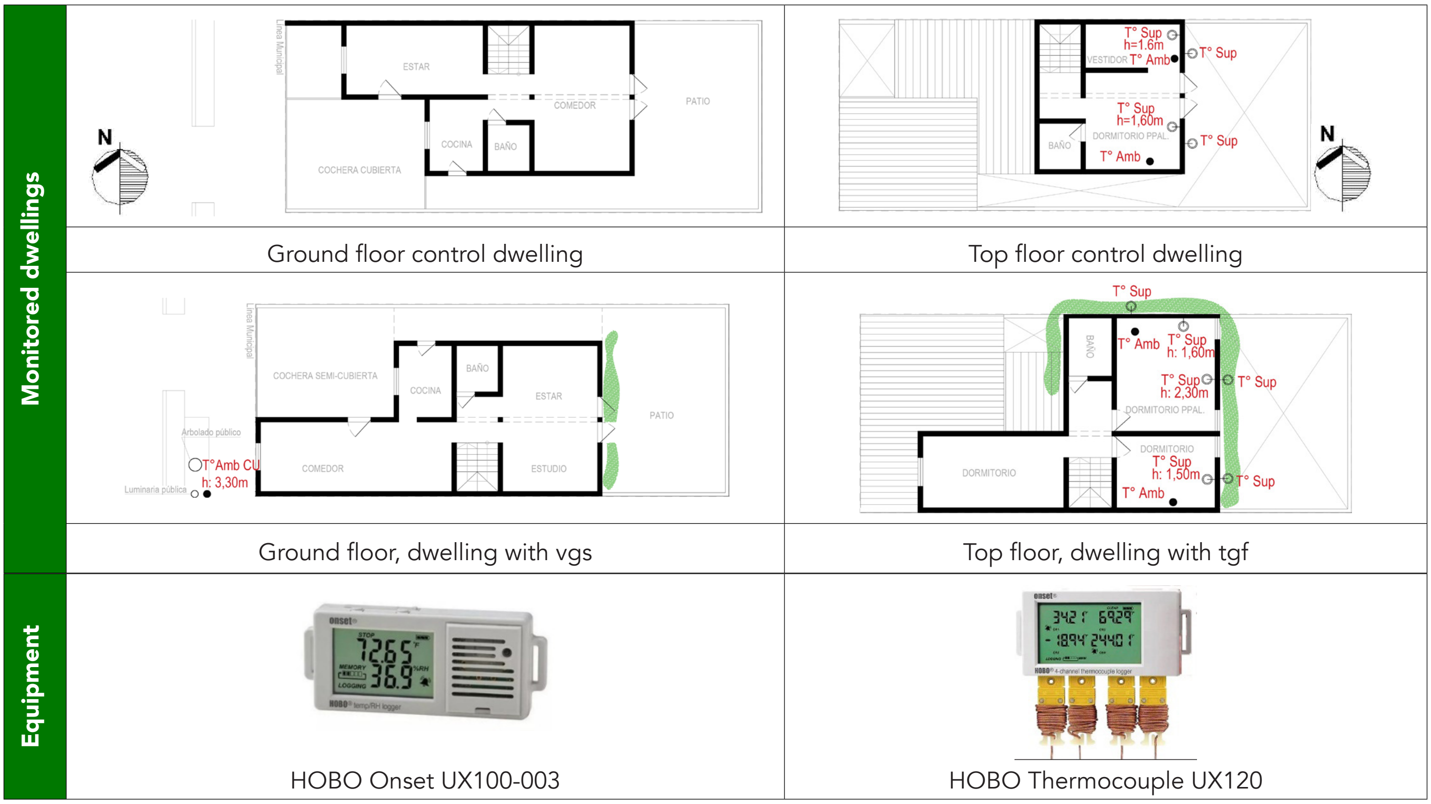

Figure 5. Case studies: location of sensors and equipment used.Fuente: Elaboración de los autores.Source: Preparation by the authors.

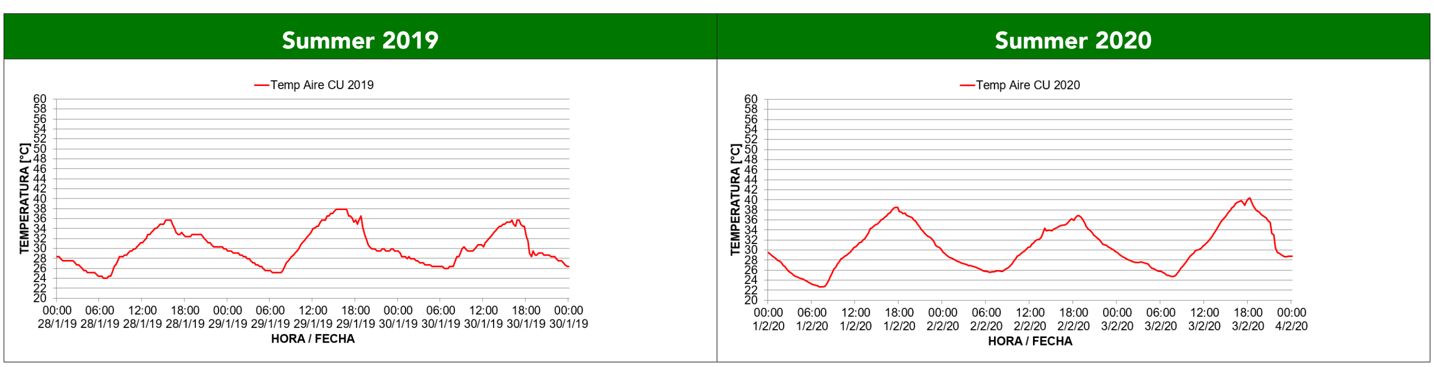

Figure 6. Air temperature in the urban canyon for the chosen days. Source: Preparation by the authors.

SELECTION OF ANALYSIS DAYS

For the purposes of comparatively analyzing the thermal response of the case studies evaluated with and without TGF, days were chosen, whose characteristics were representative of a typical summer day of the local microclimate, within the 30-day period where the measurements were recorded. As a result of this, the selection criteria were the following: highest and lowest temperatures, high heliophania and low wind speed. The days chosen in each period were: from January 28th to 30th 2019, and from February 1st to 3rd 2020. Figure 6 presents the air temperature behavior in the urban canyon for the days of analysis. The shape of the curve reflects that the analyzed days have a similar behavior regarding the kurtosis of the outdoor air temperature curve as well as its amplitude. It is checked that the maximum and minimum temperature peaks match in magnitude and hourly occurrence over time.

Considering the behavior of the curves and the quantitative analysis of the data for the 2019 period, daily temperature ranges that vary from 35.7°C to 37.9°C are seen for the maximum, and between 24.0°C and 26.0°C for the minimum. In the days corresponding to summer 2020, daily temperature values that oscillate between 36.8°C and 40.4°C are

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	Max. Temp.	Min. Temp	Total av. Temp.	Min. Av. Temp	Max. Av. Tempo	Av. Amplitude
2019 Period: 28/01 - 30/01	37.9	24.0	30.4	25.0	36.4	11.4
2020 Period: 01/02 - 03/02	404	22.7	30.9	24.3	38.6	14.2

Table 1. Average maximum, mean and minimum temperatures for the analyzed periods.

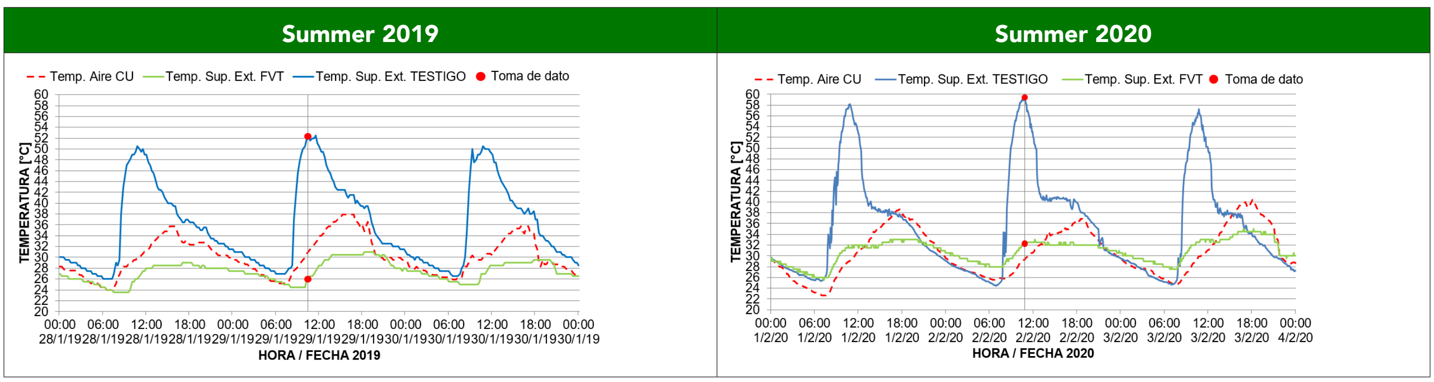

Figure 7. Outdoor surface temperature: control case and case with east-facing TGF. Source: Preparation by the authors.

seen for the maximums, and between 22.7°C and 25.6°C, for the minimums (Table 1).

Taking the average temperature values, magnitudes of 36.4°C in the maximums and 25.0°C in the minimums are seen for the 2019 period, and values of 38.5°C in the maximums and 24.3°C in the minimums, for the 2020 period are seen. Differences of around 2.1°C are confirmed regarding average maximum temperatures, and differences of 0.7°C with respect to the average minimum temperatures between the two periods considered are also confirmed. Finally, using the average mean temperature values, magnitudes of 30.4°C and 30.9°C were found for the time periods of 2019 and 2020, respectively. It is seen that both periods record differences of around 0.5°C (Table 1).

Considering the daily thermal amplitude variable, the temperature range oscillates between 9.8°C and 12.7°C, for the first period, and between 11.2°C and 15.8°C for the second one. On average, the thermal amplitude registers magnitudes of 11.4°C and 14.2°C for the 2019 and 2020 periods, respectively (Table 1).

RESULTS AND DISCUSSION

Continuing with the study, three variables were chosen, incidence on the thermal-energy performance of the cases being analyzed – from the database collated over the chosen days of summer 2019 and 2020: outdoor surface temperature, indoor surface temperature, and indoor room temperature of homolog spaces. Said variables were analyzed in terms of the temperature difference between both cases: case with TGF and control case. This is outlined below.

OUTDOOR SURFACE TEMPERATURE: CASE WITH TGF VS. CONTROL CASE

In order to recognize potential impacts of using vegetation on east-facing outdoor masonry walls, the outdoor surface temperatures of the case with TGF (green curve), the control case (blue curve) and the behavior of the outdoor air temperature (red curve) were compared (Figure 7).

The TGF case has lower outdoor surface temperatures than the control case during all daytime hours. The maximum outdoor surface temperature reductions were 26.5°C and 27.4°C, for the first and second period, respectively. The temperature difference peaks are seen, in both periods, between 10:30 am and 10:45 am, on days with clear skies (Figure 8). This shows that the outdoor surface temperature is essentially controlled by the radiation phenomenon, bearing in mind the orientation of the wall, east. The results are higher than magnitudes found by Vox, Blanco and Schettini (2018) and Hoelscher, Nehls, Jänicke and Wessolek (2016), which range between 9.0°C and 15.5°C (North-facing TGF in a Csa Mediterranean hot summer climate type, Northeast-facing TGF in a DFb warm summer climate type, respectively).

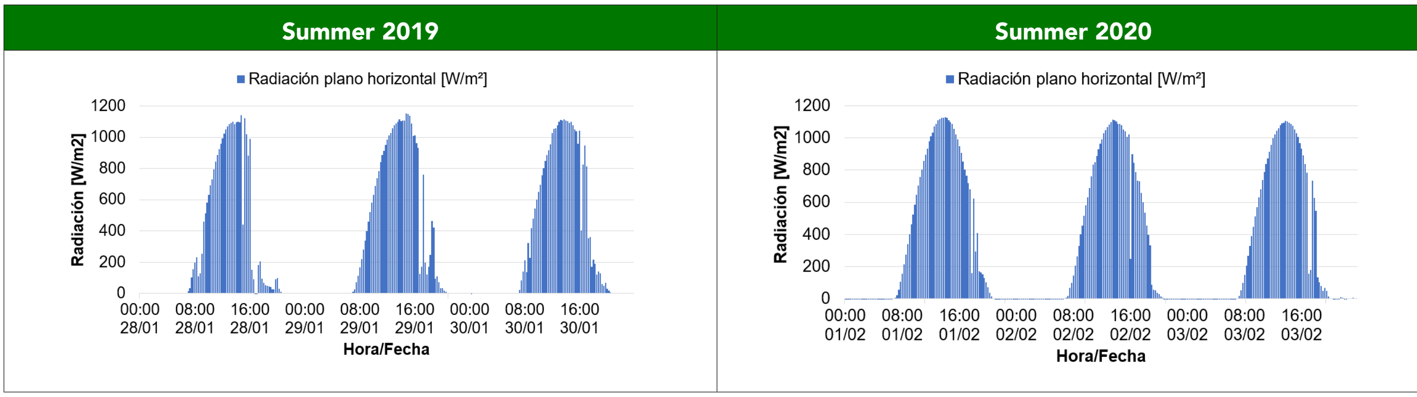

Figure 8. Global irradiance on the horizontal plane for both study periods. Source: Preparation by the authors.

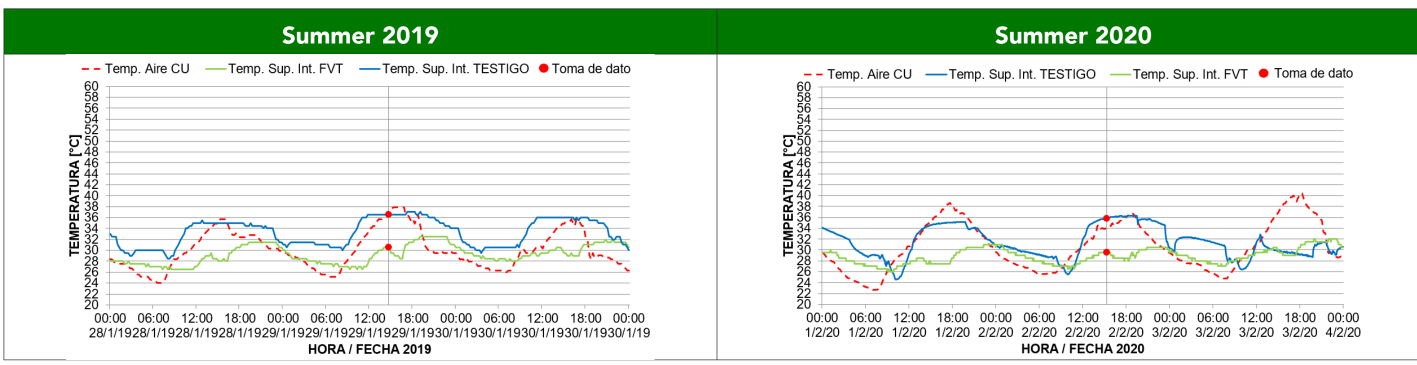

Figure 9. Indoor surface temperature: control case and case with VGS, east facing. Source: Preparation by the authors.

The analysis of the surface temperature curves of the wall with TGF shows a thermal amplitude that oscillates around 6°C on average in both periods measured. On the contrary, the curve corresponding to the control wall registers a thermal amplitude of 24°C on average in the first period and of 31°C in the second period. This is because in the second period measured, 2020, higher temperatures were recorded. The behavior of the wall covered with vegetation shows attenuated maximums and minimums which reflect the conservative capacity of the green wall, compared to the behavior of the insulating material.

In the behavior of the curves of Figure 6, it is seen that the cooling effect produced by the TGF occurs throughout all daytime hours in both periods, where the outdoor surfaces of the walls are always colder than the control case. While, on the other hand, the case with TGF has higher outdoor surface temperatures compared to the control case, during the night of the 2020 period. This magnitude records a maximum of 4.1°C higher on the surface covered with vegetation, compared to the control wall. As a result, the wall with TGF is fresher during the day and warmer during the night, compared to the control in this period. These results are because of the higher thermal amplitude recorded in the summer of 2020, where the insulating effect of the wall with TGF can be perceived during the night. However, it must be considered that the maximum cooling magnitude on the wall with TGF is 6.7 times higher than the maximum heating magnitude of the control case, and it happens at times where the outdoor ambient temperature registers its highest values.

With the purpose of checking the response of the outdoor surface temperatures on control and TGF walls when facing different outdoor climate conditions, and considering that the summer of 2020 has higher average and maximum temperatures than summer 2019, a comparison was made between the averages of the maximum daily magnitudes of this variable. The averages of the maximums recorded on the control wall and the wall with TGF were compared in the two periods. The control wall has, during the entire 2020 period, a 7.3°C increase in the average maximum outdoor surface temperatures, compared to 2019; while the TGF wall has, during the entire 2020 period, a 4.5°C increase in the average maximum outdoor surface temperature compared to 2019. Bearing in mind that the average maximum air temperature increased 2.2°C between the periods, it can be inferred that the harder the summer is, the greater the impact of the TGF is.

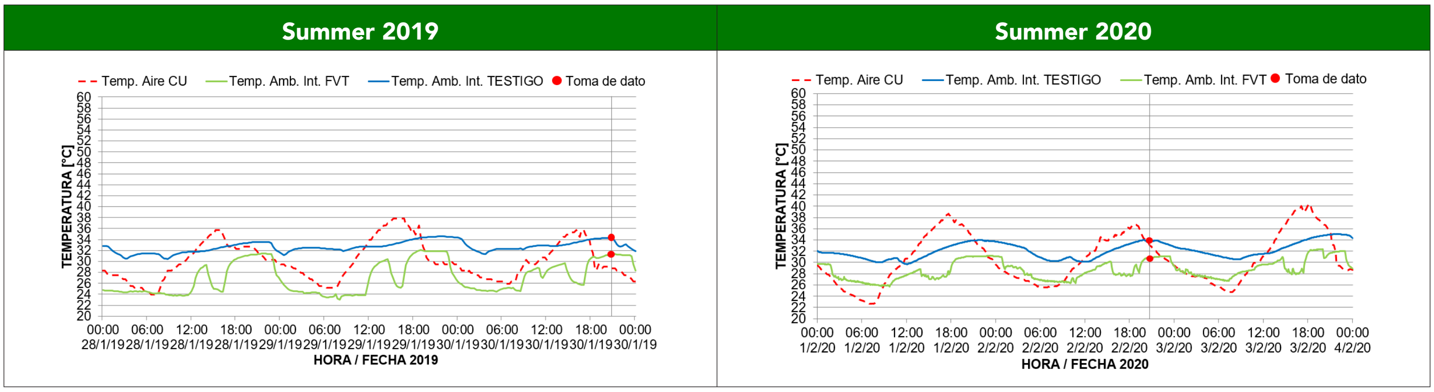

Figure 10. Indoor room temperature: control case and case with VGS, both east-facing.Source: Preparation by the authors.

INDOOR SURFACE TEMPERATURE: TGF CASE VS. CONTROL CASE

The indoor surface temperatures were measured to determine the thermal impact of using vegetation inside the evaluated dwellings. Figure 9 illustrates the behavior of the indoor surface temperature of the wall with TGF (green curve), the control case (blue curve) and the outdoor air temperature (red curve).

The case with TGF shows the indoor surface temperatures compared to the control case during all daytime hours, with maximum reductions of 6.0°C and 6.5°C for the 2019 and 2020 cycles, respectively. These temperature differences are seen in both periods between 2:45 pm and 3:45pm: one and two hours after the solar midday. This delay found, in respect to the maximum radiation time, can be interpreted as a consequence of the thermal inertia of the construction setup of the walls, which is coherent with the typical behavior of the mass materials of the envelope. This underscores that, just as with the outdoor surface temperature, the indoor surface temperature is greatly conditioned by the radiative phenomenon for this east-facing wall. The results are higher than the magnitudes found by Hoelscher et al. (2016) and Susorova et al (2013), which oscillate between 1.7°C and 2.0°C (West-facing TGF in DFb warm summer climate type, North-facing TGF in Dfa hot summer continental climate type, respectively).

Unlike the analysis of the outdoor surface temperature, the cooling magnitudes on the indoor surfaces of the walls, produced by the presence of vegetation, occur during daytime and nighttime hours in both periods. That is to say, the cooling effects of the TGF have an impact on the inside of the dwellings also during times without solar radiation. Now, it is important to mention that the indoor surface temperatures are affected by the use of air conditioning at times where the outdoor environmental temperature moves away from the comfort temperature. This is the result of monitoring real cases in use conditions in the warm season. It is because of this that, in the interest of considering the objective of this work, the temperature differences were taken in the absence of air conditioning.

INDOOR ROOM TEMPERATURE: TGF CASE VS. CONTROL CASE

Figure 10 graphically shows the behavior of the indoor room temperature in two homolog spaces between the TGF (green curve), the control (blue curve) and the outdoor air temperature (red curve) cases for the two periods measured.

The analysis of indoor room temperature allows identifying that the temperature of the TGF case is lower than the control one, with maximum differences of between 2.9°C and 3.1°C during all hours of the day in the two measurement cycles. Just as seen in the surface temperature analysis, the differences are greater than those found by Kontoleon and Eumorfopoulou (2010), which were around 0.5°C (east-facing TGF with a Cfb soft summer template oceanic climate type). Meanwhile Hoelscher et al. (2016) and Perini, Ottelé, Fraaij, Haas and Raiteri (2011) did not find effects of the TGF on the air temperature in indoor spaces.

The indoor room temperature in the dwelling with TGF reveals average reductions of 3°C compared to the control case. This result can be interpreted as the magnitude of the TGF use impact on the sensitive heat of a dwelling. Just as in the case of the indoor surface temperature, the use of air-conditioning is seen in the behavior of the indoor temperature curve. It is for this reason that, again in this analysis, the data were taken in periods without artificial air conditioning of the spaces.

CONCLUSION

The work presented evaluated the impact of east-facing TGF, on the indoor and outdoor temperatures, and the indoor room temperature in dwellings built from baked brick and reinforced concrete structures. The study was performed in the Metropolitan Area of Mendoza, during the summer, on a representative analysis universe, from the morphological and technological point of view, of single-family terraced dwellings in the study area.

Quantitatively, the research shows a potential to reduce outdoor surface temperatures on the envelopes of buildings by up to 27.4°C and by 6.5°C on indoor surface temperatures. These benefits are due to the effect of the green structure on the wall compared to the full exposure of the control wall. Considering the results found in international literature for other climates and the same construction technology – bricks and reinforced concrete – it is seen that the application of TGF, as a strategy to improve the thermal behavior of indoor spaces, is more efficient in arid climates.

In addition, the temperature variations between the two periods measured express that, on facing the harshest outdoor conditions, the impact of TGF is greater in the attenuation of indoor and outdoor surface temperatures.

The comparison of the behavior of the wall surface temperature curves with TGF compared to the control wall, show the attenuation capacities of the maximum and minimum temperatures that result from the conservative nature of the TGF, which is comparable with that of an insulating material. However, the TGF offer additional advantages compared to the application of synthetic materials for thermal conservation, linked to ecosystemic benefits and contributions to people's health. From this conclusion, the need is seen that, in future research, the additional benefits of green strategies are considered to measure their efficiency regarding traditionally used insulation strategies.

Regarding room temperatures, reductions of around 2.9°C and 3.1°C were recorded in the 2020 and 2019 periods, respectively, in the dwelling with TGF compared to the control case. Likewise, it was seen that the average magnitude of the impact on the sensitive heat of the dwelling is around 3°C. The indoor temperature reduction values reached in this work, just like those obtained regarding the reduction of surface temperatures, have a greater magnitude compared to the findings in scientific literature, in similar experiences evaluated in other climates (0.5°C). These results demonstrate the value of using the strategy to decrease indoor temperatures and to approach comfort conditions for inhabitable spaces inside buildings in arid climates.

Summarizing, this research represents a concrete contribution to the development of knowledge about the implementation of VGS in buildings located in desert arid type climate areas (BWk - Köppen-Geiger). In this sense, the results found demonstrate the potential of a suitable greenery technology regarding its efficiency to reduce temperatures and contribute to energy savings, as a result of a lower energy demand for the thermal conditioning of indoor spaces. That is to say, it presents an alternative simple application strategy for building envelopes that tends to not just guarantee the sustainability of the habitat in harsh climatic contexts, but also to improve the quality of life of the built environment within the framework of a sustainable development.

In future stages, it is foreseen to increase the number of case studies, assess the impact associated to other construction technologies and to the use of different species for the TGF. The end goal is to broaden the scope of this research, and to generalize results that contribute towards fostering the use of TGF as a design tool to reduce indoor temperatures in the built setting and their impacts on a building, urban and global scale.

ACKNOWLEDGMENTS

The authors would like to thank the National Scientific and Technical Research Council (CONICET) and the National Agency for Scientific and Technological Promotion (ANPCYT) for the financing received to carry out this research. They would also like to thank the owners of the dwellings, Miguel Martí and Rodrigo Benítez who allowed the monitoring of the case studies.

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Revista Hábitat Sustentable Vol. 10, N°. 2. ISSN 0719 - 0700 / Págs. 94 -105
https://doi.org/10.22320/07190700.2020.10.02.07

Recibido 31/08/2020
Aceptado 12/12/2020

IMPROVEMENTS IN THE ENERGY PERFORMANCE OF BUILDINGS IN SUMMER, THROUGH THE INTEGRATION OF VENTILATED ENVELOPES ON NORTH-FACING FACADES AND ROOFS. THE CASE OF MENDOZA, ARGENTINA.

MEJORAS EN EL DESEMPEÑO ENERGÉTICO DE EDIFICIOS EN VERANO MEDIANTE LA INTEGRACIÓN DE ENVOLVENTES VENTILADAS EN FACHADAS NORTE Y CUBIERTAS. EL CASO DE MENDOZA, ARGENTINA.

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RESUMEN

La propuesta de medidas de eficiencia energética en el sector residencial de Argentina requiere el análisis de las posibilidades arquitectónicas de rehabilitación edilicia con tecnologías que disminuyan los consumos energéticos, factibles de implementarse a nivel local. En regiones con alto nivel de radiación solar, como es el caso de la ciudad de Mendoza, pueden reducirse los flujos de calor transmitidos al interior mediante la ventilación natural de las capas en la envolvente -tanto en fachadas como en cubiertas-, obteniéndose así importantes ahorros en los consumos para refrigeración. El presente trabajo evalúa el potencial de mejora con la integración de envolventes ventiladas. La metodología del trabajo se estructura en dos etapas: i) relevamiento de edificios residenciales, según la tipología morfológica, y análisis de las posibilidades de rehabilitación con fachada ventilada, de acuerdo a las superficies de envolvente expuesta por orientación; ii) simulación de un caso de estudio -previamente validado con mediciones in situ- con el software EnergyPlus. Al integrar fachadas y cubiertas ventiladas se lograron importantes ahorros energéticos del orden del 32%, considerando al edificio sin usuarios (desocupado). Para el caso de las unidades del último piso, con cubiertas expuestas al exterior se registraron ahorros energéticos del 260%.

Palabras clave
envolvente ventilada, rehabilitación edilicia, eficiencia energética, consumos para refrigeración

ABSTRACT

The proposal of energy efficiency measures in the residential sector in Argentina requires analyzing the architectonic possibilities of building rehabilitation using technologies that reduce energy consumption, that are feasible to implement locally. In regions with high solar radiation levels, as is the case of the city of Mendoza, heat fluxes transmitted inside can be reduced by the natural ventilation of the layers in the envelope, both on facades and roofs, thus obtaining significant savings in consumption for cooling purposes. This work evaluates the potential for improvement with the integration of ventilated envelopes. The work methodology is structured in two stages: i) survey of residential buildings by morphological typology and analysis of rehabilitation possibilities with ventilated facades, considering the exposed envelope surfaces by orientation; ii) simulation of a case study - previously validated with onsite measurements - using the EnergyPlus software. On integrating ventilated facades and roofs important energy savings of around 32% were achieved, considering the building without users (unoccupied). In the case of units on the top floor, with roofs exposed to the outside, energy savings of 260% were recorded.

Keywords
Ventilated envelope, Building rehabilitation, Energy efficiency, Cooling consumption

INTRODUCTION

Facing the context of a continuous growth in energy prices around the world and looking to support global efforts to mitigate global warming, building rehabilitation emerges as a known strategy for improving the energy efficiency of buildings. The rehabilitation of the envelope presents benefits, not just in respect to the energy savings of spaces, the improvement of indoor microclimate and the reduction of contaminating emissions obtained, but also for the technical and economic feasibility of a project (Ascionea, Biancoa, De Masib & Vanolib, 2013). In this regard, valid indicators have been generated starting from the creation of tools, through standards (ISO and ASTM), contributing economic knowledge for the implementation of energy improvements in existing single-family homes (Pérez Fargallo, Calama Rodríguez & Flores Alés, 2016). The results of the cited study indicate that, with respect to walls, the investment in a detached building is three times higher than a dwelling between party walls with interior insulation.

Research on passive strategies in the envelope has increased considerably, offering an important contribution to architecture. Background information, in this sense, includes a series of design and construction recommendations, that cover both those referring to transmittance values, and to the incorporation of weighting factors considering the position of the insulation and thermal mass (Damico *et al.*, 2012; Leccese, Salvadori, Asdrubali & Gori, 2018; Albayyaa, Hagare & Saha, 2019; Raimundo, Saraiva & Oliveira, 2020; Cabeza & Gracia, 2021). On the other hand, when considering global warming and climate forecasts, generic adaptation architectonic design strategies have been studied from the passive point of view, determining climate scenarios for 2020, 2050 and 2080 (Rubio-Bellido, Pulido-Arcas, & Ureta-Gragera, 2015; Filippín, Ricard, Flores Larsen & Santamouris, 2017; Haddad *et al.*, 2020).

As for the regions with a high level of solar radiation, one of the feasibly applicable strategies to improve the thermo-energy conditions in periods with high temperatures, is reducing the heat flows transmitted inside through the natural ventilation of the envelope's layers, both on façades and roofs, obtaining savings in air-conditioning consumption that can reach up to 80% (Domínguez Delgado, Durand Neyra & Domínguez Torres, 2013; Gagliano, Patania, Nocera, Ferlito & Galesi, 2012). The ventilated envelope system is formed by an air chamber bordered by two opaque sheets, into which the outside air freely accesses. The ventilated chamber creates a "chimney effect" caused by the heating of the outside sheet, which is why a variation of the internal air density of the chamber is produced compared to the ambient temperature outside, with the resulting movement by natural convection. During summer, the external sheet blocks solar radiation, reducing the surface temperature of the inside sheet; meanwhile, in winter, the air movement in the chamber and its resulting fall in temperature, allows the evacuation of water vapor, reducing the possibility of interstitial condensation (Suárez & Molina, 2015). This is due to the increase of the heat flow inside the chamber, generated by direct solar radiation that has a bearing on the outside sheet and the resulting heat transfers through conduction and convection in the air chamber. In addition, this improvement is due to the possibility of continuous thermal insulation on the external face of the interior enclosure and the fact of having a protection to confront the direct solar radiation on the enclosure that limits the inhabitable space.

Ventilated facades, with regard to the vertical envelope, comprise a light or traditional masonry inside sheet, and an outside one, comprising plates that may be made from a great variety of materials, sizes and colors, normally with open joints (see Figure 1). In terms of background information at an academic level, diverse studies have addressed the issue, with different study methods which, at the same time, can be combined with each other. Most of the works are made through dynamic computer simulations (Balocco, 2002; Balocco, 2004; Patania, Gagliano, Nocera, Ferlito & Galesi, 2010; San Juan, Suárez, González, Pistono & Blanco, 2011; Suárez & Molina, 2015; Peci López & Ruiz de Adana Santiago, 2015, Gagliano, Nocera & Aneli, 2016), although in some cases, experimental prototypes have been created (Sandberg & Moshfegh, 1996; Peci López, Jensen, Heiselberg & Ruiz de Adana Santiago, 2012; Sánchez, Giacola, Suárez, Blanco & Heras, 2017) and in others, work has been done by monitoring real buildings in use (Stazi, Tomassoni, Veglio & Di Perna, 2011; Aparicio Fernández, Vivanco, Ferrer Gisbert & Royo Pastor, 2014; Gregorio Atem, 2016). The results of the thermal performance of the system under study in the summer period, show reductions of around 58% of the thermal load obtained on using a ventilated façade in comparison to a façade without ventilation (Fantucci, Marinosci, Serra & Carbonaro, 2017), as well as important reductions in energy consumption for air-conditioning, with energy savings rates for passive cooling of between 35% and 80% (Domínguez Delgado *et al.,* 2013).

The result of experimental studies made in summer, shows that the orientation to the equator has the best performance regarding air flow and speed values in the ventilated chamber (Balter, Pardal, Paricio & Ganem, 2019; Stazi *et al,* 2011). Likewise, a thermodynamic analysis of the performance in the chamber, with maximum air speeds of between 0.45m/s and 1.9m/s,

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https://doi.org/10.22320/07190700.2020.10.02.07

Figure 1. Different ventilated façade solutions in Barcelona, Spain. Source: Preparation by the Authors[1]

confirms that energy savings for cooling in summer increase as the incident solar radiation also increases (Patania *et al.*, 2010). Said work shows that the thermal and air speed differences in the chamber are mainly due to the thermophysical properties of the outside sheet: a reduction of the heat transfer that enters the building of over 40% is indicated in comparison with the same façade without ventilation.

As for the roofs, the thermal behavior of ventilated roofs, in summer, has been analyzed using computational fluid dynamic (CFD) simulations, and reductions in the heat transfers of around 50% were obtained (Gagliano *et al.*, 2012). The same methodology (CFD), that uses numerical methods and algorithms to resolve and analyze problems about fluid flows, has been used to study the influence of different parameters, thickness of the air chamber, slope of the roof, sizes of the air outlet and absorption coefficient of the external surface, with results that reveal the important influence of the chamber's thickness on the delays of indoor room temperature, which is why a thickness of 100mm is recommended when looking to improve the air flow speed in the ventilated chamber (Li, Zheng, Liu, Qi & Liu, 2016).

Apart from the physical and constructive properties of the system's elements, the air movement in the chamber is an important factor in its efficient performance. In this sense, the background information shows that, although the main variables that affect said movement are solar radiation and external air speed, the width of the chamber is also influential. In the work of Balocco (2002), increases of air flow in respect to this width are obtained, with reductions in summer of the overheating due to radiation of 27% with a 35cm chamber, while reductions with a 7cm chamber are of 7%. In any case, many works agree that it is important to make a detailed analysis of the context before facing a new project or rehabilitation. For this, the local climate, the specific design of the enclosure, the physical and operational differences of the construction (air entry and exit locations, chamber thickness, physical properties of the materials), the desired use and comfort of the building, as well as the primary energy cost and the CO_2 emissions, must be considered (Ibáñez-Puy, Vidaurre-Arbizu, Sacristán-Fernández & Martín-Gómez, 2017; Elarga, De Carli & Zarrella, 2015; Aparicio Fernández *et al.*, 2014; Peci López *et al.*, 2012; San Juan *et al.*, 2011).

1 The images of the buildings were obtained by Cristina Pardal PhD, of the Architecture Technology Department of the Polytechnic University of Catalonia.

In consideration of the study's context, it must be indicated that central-western Argentina has an abundant solar resource. Specifically, Mendoza is located in a continental cold arid area, according to the climate classification of Köppen and Geiger (1936), with considerable differentiations in seasonal and daily temperatures (from 10 to 20°C). With regard to the solar resource, the city has clear skies for 76% of the year, with a mean global radiation in December (summer) on the horizontal surface of 25.4 MJ/m^2 a day and 9.10 MJ/m^2 a day in June (winter). This condition represents an opportunity for the passive conditioning of spaces and, in this framework, the opaque envelope systems with natural ventilation are a feasible alternative to be incorporated, due to their good performance in areas with high radiation.

From the point of view of urban structure, the city of Mendoza (32° 40' LS - 68° 51' LW) is characterized on being an oasis-city (Bórmida, 1984), because of its intense forestation set in an arid area. The city defines, from an environmental approach, two high levels given by said forestation: with and without trees. In this context, indoor spaces located up until the third floor, under the tree canopy, have a moderate micro-climatic situation and are thermally and energetically benefitted. Meanwhile, in spaces on higher floors, from the fourth one up, i.e., above the canopy, the situation is more extreme and the consumption for air-conditioning is higher due to the complete exposure of their envelopes. Even when high-rise constructions of the city, built in the last 15 years, tend to record high percentages of transparent surface on the envelope, most residential buildings in Mendoza, correspond to a mainly opaque material. However, these do not have insulating materials and in rarely have solar control elements on the envelope.

Said situation, which is added to the growing use of ventilated envelope systems in European countries, allows setting questions about the possibility of inserting these systems in our study context: a zone with high solar resources. The comprehensive approach of the topic requires a process that considers analysis from different perspectives: on one hand, from the energy efficiency of the envelope system following the region's climatic conditions, both for building rehabilitation and for new buildings; and, on the other, from the technological availability and the legal possibilities in force to suitably incorporate ventilated systems on their different urban and social scales . In this work, the first of the approaches mentioned is carried out, from which the following objective is defined: Assessing the formal possibilities of rehabilitating residential buildings in the urban-architectonic high density context of the city of Mendoza, in order to reduce energy loads for cooling, through the incorporation of ventilated envelopes on the north façade and roof.

METHODOLOGY

The work methodology is structured in two stages: i) surveying residential buildings by morphological typology and analysis of the possibility of rehabilitation with a ventilated façade, considering the envelope surfaces exposed by orientation; ii) simulation of a case study, previously validated with onsite measurements using the *EnergyPlus* software.

SURVEYING AND ANALYSIS OF BUILDING REHABILITATION WITH VENTILATED FAÇADE BY ORIENTATION

The study area corresponds, according to the Building Code of the city of Mendoza, to Central Zone 2, a zone with a higher high-rise building density of a mainly residential nature. Its population density is estimated at more than 800 inhabit/ha. The zone has three of the main squares in the city's grid plan. There are 14 main roads, 12 of which are 20 meters wide and 2 of them, 30 meters wide. These form a total of 32 blocks. In order to evaluate the possibility of rehabilitating façades considering their exposed orientation, constructions that exceeded the maximum height of the tree's canopy were surveyed (characteristic trait of the "oasis-city" of Mendoza), namely: buildings that have 5 or more floors (starting from GF + 4). According to the morphology of high-rise buildings, in Mendoza there are three typologies, as per the building regulations in force at the time of their construction: 1. High-rise building between party walls; 2. Tower; and 3. Foundation and tower.

Figure 2 shows images of Mendoza and the surveyed building area, with a sample group of 67 residential buildings, 26 of which belong to the building typology of high-rise between party walls; 15 of detached tower; and the other 26, the foundation and tower typology.

2 In the area of Mendoza, new technologies with local innovation levels find limitations to comply with regulatory requirements, as they do not always have the backing of the institutions involved for their definitive approval. In this scenario, only formal technologies, a large part of which, in our case, are foreign in origin, meet these requirements, but in general, these are of a selective implementation given their scale and high costs. The possibilities of including other feasible technologies that can be generated and/or adapted to be implemented on a mid-rise or low-rise building, are limited.

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https://doi.org/10.22320/07190700.2020.10.02.07

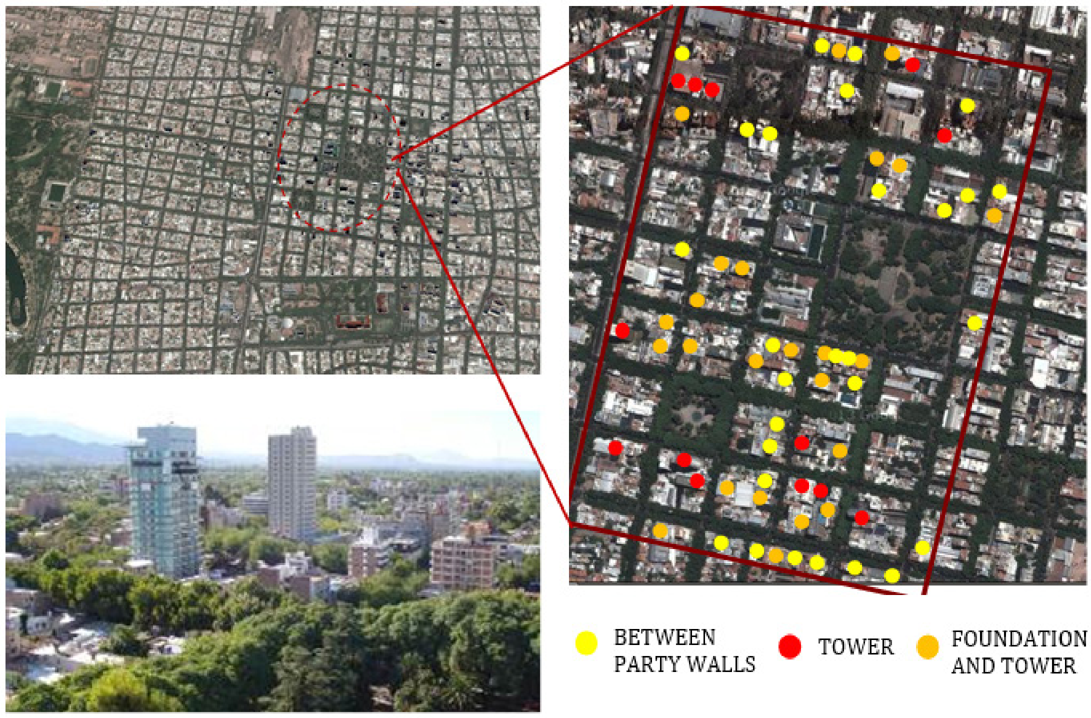

Figure 2. Images of the city of Mendoza. Area of high-rise buildings surveyed. Source: Preparation of the authors.

Starting from the survey of the cases by morphological typology, the following variables were analyzed in each one of the buildings (Table 1): floor height, front façades exposed by orientation, opaque material of the vertical envelope, opaque and transparent envelope surface percentage by façade and orientation and window-to-wall ratio (WWR). It is worth clarifying that some of the cases surveyed are located on corners, so they have front façades on two orientations.

After this, and to diagnose the possibilities of rehabilitation by façade, the envelope's conditions were analyzed by surveying the amount of surface exposed by orientation. From this analysis, the following evaluations emerged: it is considered possible to rehabilitate facades with more than 50% of continuous high-rise surfaces without window openings, given that, on the other hand, the benefit of the ventilated chamber would be lost. However, in cases that have exposed facades with more than 50% of openings or elements that impede the continuity of the chamber (such as balconies), the implementation of the system on these faces could be considered, merely as cladding, to have buildings with a homogeneous and balanced image. In the same way, high-rise buildings belonging the high-rise buildings between party walls typology, built following the pre-1970 regulations, have blind facades on orientations that are next to adjoining land. Today, given that the current building code does not allow constructions above 10 m built side-by-side, these blind facades have the possibility of being intervened and rehabilitated, with the resulting energy benefits. However, there is the risk of having an adjoining tower-block at a minimum distance of 3 meters, with which radiation incidence would be blocked. Therefore, the following conditions are classified, considering each orientation.

- Possible rehabilitation with ventilated façade.
- Possible rehabilitation with ventilated façade on adjoining boundary.
- Intervention impossible.

Figure 3 presents the results given by the survey. In the high-rise between party walls building typology, it is possible to rehabilitate facades in 14 cases, of which only 6 have possibilities to rehabilitate the north-façade; 2 of them can also see the east façade rehabilitated. In the case of the Tower typology, it is possible to rehabilitate 7 buildings, 4 of which allow the north façade's rehabilitation. In those from the foundation and tower typology, none of the cases have possibilities of rehabilitating the north façade. It is important to clarify that the criterion defined to not intervene, is because in some buildings, those with facades of over 50% of glazed surfaces or with balconies across the façade would block the continuous flow of air in the chamber. Now, in other cases, the criterion is based on these being buildings with a marked architectonic trend

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https://doi.org/10.22320/07190700.2020.10.02.07

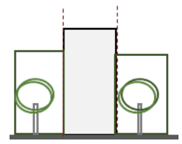
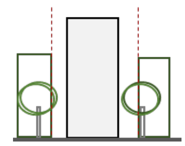
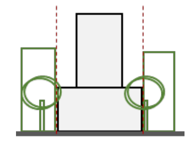
VARIABLES ANALYSIS	**TYPOLOGY**	**BETWEEN PARTY WALLS**				**TOWER**				**FOUNDATION & TOWER**			
		 26 buildings (32 front facades)				 15 cases (16 front facades)				 26 cases (33 front facades)			
Height (floors)	> 7	21				11				16			
	7 a 10	5				1				7			
	< 10	-				3				3			
Front facades exposed by orientation	North	13				5				11			
	South	7				6				3			
	East	7				2				6			
	West	5				2				6			
Opaque materiality of vertical envelope	Brick + whitewash	21				11				17			
	Brick + ceramic cladding	1				-				-			
	Brick + stone cladding	2				2				2			
	Visible Brick	-				-				4			
	Reinforced concrete (RC)	1				-				3			
	RC + brick + stone clad.	1				-				-			
	RC + plaster plates	-				2				-			
Window to Wall ratio (WWR)	0 a 0.19	1				1				1			
	0.2 a 0.39	24				11				20			
	0.4 a 0.59	1				2				2			
	0.6 a 0.79	-				-				3			
	0.8 a 1	-				1				-			
% of opaque envelope surf. exposed by facade		N	S	E	W	N	S	E	W	N	S	E	O
	> 40	-	-	-	-	-	-	-	1	1	-	2	-
	40 a 60	-	-	-	-	1	-	-	-	-	1	1	1
	60 a 80	12	6	4	5	4	4	2	1	10	1	5	5
	< 80	1	1	3	-	1	1	-	1	1	1	1	3
% of transp. envelope exposed by facade	> 40	12	7	7	5	3	6	2	2	11	2	6	8
	40 a 60	1	-	-	-	2	-	-	-	-	1	1	1
	60 a 80	-	-	-	-	-	-	-	-	1	-	2	-
	< 80	-	-	-	-	-	-	-	1	-	-	-	-

Table 1. Variables analyzed of the building typologies subject to study.Source: Preparation by the authors.

(brutalism, postmodernism) or material (natural rock cladding). Here, the rehabilitation would remove the architectonic value from the buildings. Likewise, the south façade, in the southern hemisphere, receives only 2.3% direct solar radiation in comparison to the north façade. For this reason, buildings where it is not possible to implement the system being studied, are not considered.

SIMULATION OF THE CASE AUDITED IN ENERGYPLUS

This work takes as a case study, one of the buildings analyzed as possible to be rehabilitated (case 4 in Figure 3), corresponding to the high-rise between party walls building typology (see Figure 4). Although the building analyzed is north-facing, and with possibilities to rehabilitate said façade, the application of the methodology adopted is feasible to be replicated both for other locations, and for other buildings with different orientations.

The building has a total height of 25 m (ground floor + 7). In terms of the envelope's material, it has 0.30m hollow ceramic brick outside wall with paint and whitewash and no insulation, and the roofs comprise reinforced concrete slabs. The windows are simple 4mm glass and wooden carpentry. The dwellings' inside divisions are made with 0.10m thick ceramic brick. The building has, on its front façade, 1.20m deep balconies that form overhangs, and has sliding blinds with white latticework on all the openings. As for the exposed envelope percentage, it has a Window-to-Wall (WWR) ratio of 0.30.

Concretely, hygro-thermal measurements were made on the inside and outside of the building, specifically in the first and fifth floor dwellings. Onsite monitoring was made over a year, in periods of twenty and thirty days, in each of the four seasons. ONSET's HOBO U.12 temperature and humidity dataloggers were used, with recording intervals of every 15 minutes, simultaneous in all the instruments. The global solar radiation measurements were made with a KIPP & ZONEN CM 5 pyranometer in the same periods and with the same data acquisition frequency established for the air and humidity measurements. This allowed making the adjustment and validation of the model with the *EnergyPlus* dynamic simulation software. In this study, two climate files were developed: one, for the condition given by the tree canopy, which contains the measurements made of temperature and global solar radiation (dwellings from the fourth floor up); and a second file in which the incident radiation under the urban tree line was modified, to consider the situation below the tree canopy (dwellings up to the 3rd floor, corresponding to a maximum of 12 m in height). For this, the studies performed on the degree of permeability of trees in

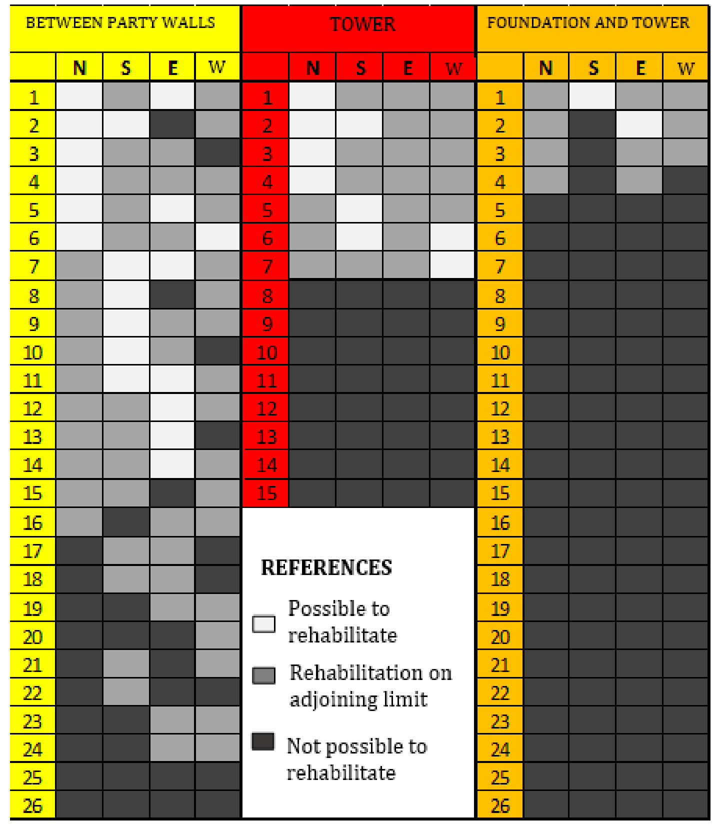


Figure 3. Results of the surveys of facades that can be rehabilitated, by building and orientation. Source: Preparation by the authors.

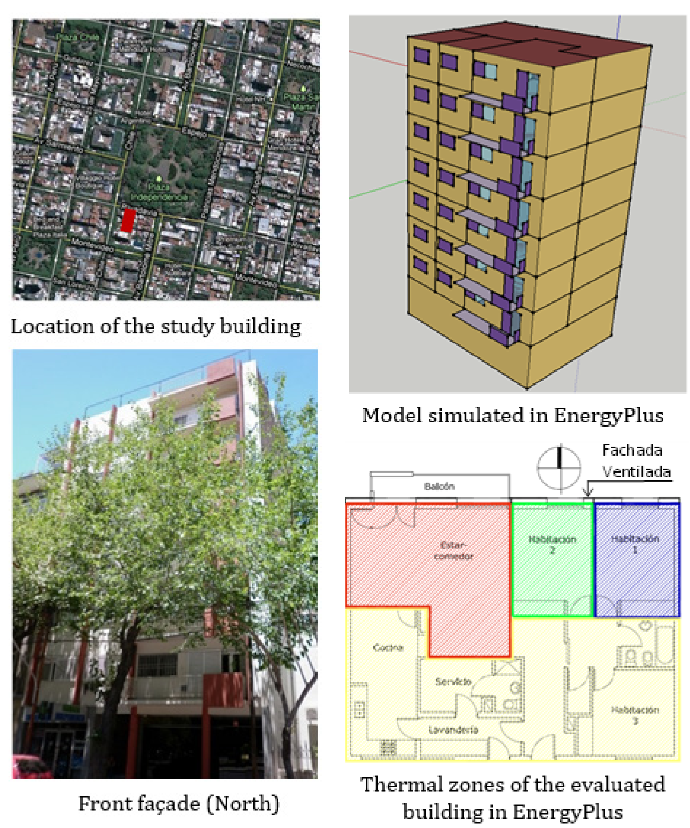


Figure 4. "High-rise building between party walls" building typology assessed. Source: Preparation by the Authors.

Properties of the exterior ventilated cavity	Measurement Unit	Value
Fraction of the openings are	Non-dimensional	1
Thermal emissivity of the exterior plate (cementitious plate type)	Non-dimensional	0.9
Solar absorption of the exterior plate (cementitious plate type)	Non-dimensional	0.1
Thermal insulation (expanded polystyrene)	m	0.05
Height of the ventilated chamber	m	2.7
Thickness of the ventilated chamber	m	0.1
Ratio between the real and projected surface	Non-dimensional	1
Roughness of the exterior surface	Non-dimensional	Soft
Holes with respect to the wind	Non-dimensional	0.25
Discharge coefficient for openings compared to the floatability flow	Non-dimensional	0.65

Table 2. Entry elements for the definition of the ventilated envelope in EnergyPlus.Source: Preparation by the authors.

central-western Argentina (Cantón, Mesa, Cortegoso, De Rosa, 2003) were considered. Said permeability to global radiation at midday corresponding to the urban tree lines there are in the case study (*Morus-Alba)* is 31.4% in summer. The specifications of said monitoring and their adjustment by simulation are found in the cited literature (Balter, Ganem & Discoli, 2016).

The ventilated envelope was incorporated on all front facades of north-facing apartments and on the roof of the top-floor dwelling (seventh). It is considered that one of the starting elements for building energy rehabilitation is the incorporation of insulation on the envelope, so, the cases assessed and compared had 5cm of expanded polystyrene on the outside of the wall. In this way, the rehabilitation under study focused particularly in assessing the effects of incorporating the ventilated chamber and the external layer of the envelope.

With said purpose, the "*Exterior Natural Vented Cavity*" object, used to trace a separate layer of the inside layer, was used inside the advanced constructions module, which allowed defining the characteristics of the cavity and the openings for outside surfaces with natural ventilation (Table 2). This object was used along with the *Other Side Conditions Model*, where the option of *Gap Convection Radiation* was set up, that provides the surrounding conditions for the thermal radiation and convection of the ventilation model modeled independently from the envelope surface.

To analyze cooling energy consumption, thermostats were programmed at 24°C for all the thermal zones being studied.

With regard to the climate file used for simulation, work was done with micro-climate data generated from the validation of data monitored onsite with the ENVI-met dynamic simulation software (Balter, Alchapar, Correa & Ganem, 2018).

RESULTS AND DISCUSSION

In Figure 5, the results of the comparison between the following cases are recorded:

- Without Ventilated Facade (Without VF): 0.30 m ceramic brick + 0.05m expanded polystyrene + exterior whitewashing. Roof: concrete slabs.
- With Ventilated Facade (With VF): 0.30 m ceramic brick + vapor barrier + 0.05m expanded polystyrene + 0.10m ventilated chamber + exterior plate. Roof: concrete slab.
- With Ventilated Roof and Façade (With VF & VR): 0.30m ceramic brick + vapor barrier + 0.05m expanded polystyrene + 0.10m ventilated chamber + exterior plate. Concrete slab + 0.10m ventilated chamber + exterior plate. Roof: concrete slabs.

The dimensional characteristics of the ventilated air chamber and the thermophysical characteristics of the exterior plate are presented in Table 2.

The incorporation of ventilation on the façade implies a reduction of energy loads for cooling, considering 24°C indoors, of around 1% as an average of the building's total. These moderate percentages are due, on one hand, to the fact that the comparison made focuses specifically on the incorporation of the ventilated chamber and the exterior

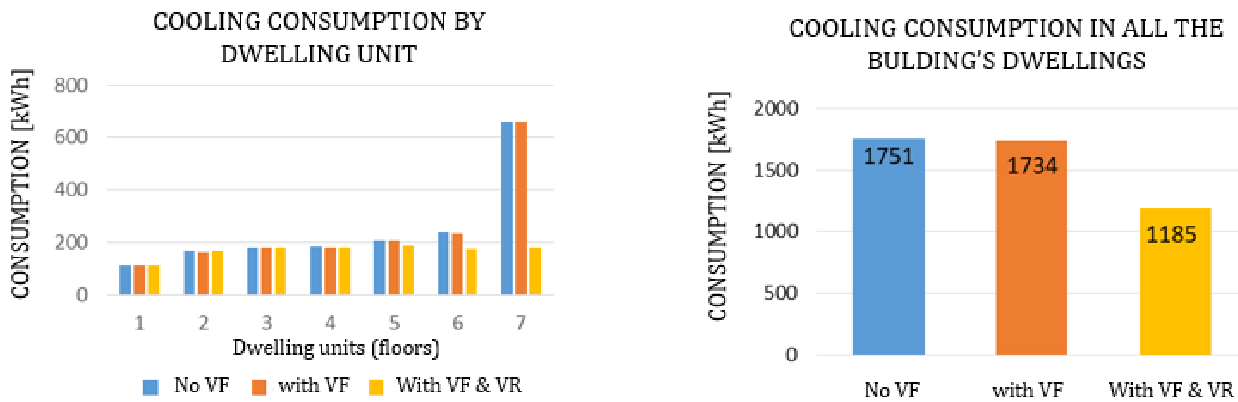


Figure 5. Energy consumption for cooling simulated in EnergyPlus. Source: Preparation by the authors.

layer, that is to say that the base case (without FV) has insulation and whitewashing on the upper part of the envelope. And, on the other hand, these reductions are affected by the compact nature of the dwellings, where only 12% of the entire envelope of each unit is north-facing. Likewise, the north facade receives only 16% of the incident radiation in summer and, in the case of Mendoza, this percentage is greatly reduced (by more than 50%) due to the urban tree lines.

All in all, on incorporating ventilation on the roof of the top-floor dwelling, located on the seventh floor, the average results of the entire building show energy improvements of 32%. In this case, the reduction in consumption of the dwellings on the first four floors is around 1.7%; a percentage that rises as the height of the dwellings goes up: on the sixth floor, this reduction is 34%, and on the top floor, 269%. This is because, above the canopy, the envelope's exposure is greater and, on reducing the heat flow on the horizontal envelope, the behavior of the envelope that has the highest exposure to solar radiation in summer, is optimized.

Regarding the constructive characteristics of the ventilated façade system, it has been shown that the increase of the air opening in the chamber implies greater energy savings for air-conditioning (Patania *et al.*, 2010). Likewise, the survey and monitoring of the air speed of buildings built with ventilated facades in Barcelona, showed that more than 70% of cases had a closed air chamber on their upper and lower openings, making the proper performance of a ventilated envelope system impossible (Balter *et al.*, 2019). The results of this work have been simulated considering interventions on the envelope in operation, which means that, in practice, it must be controlled that the upper and lower openings of the ventilated facades or the side openings of the ventilated roofs, are not closed. This demonstrates the importance of transferring knowledge about the performance of these new envelope systems, both to local building regulations, and to the industrial and construction sector, to achieve an effective guarantee of energy savings.

Another aspect to bear in mind lies in the regulations. The Argentinean IRAM standards (11600 series) work with the thermal quality and energy consumption issues of built buildings, establishing the calculation methods and the minimum values of their hygrothermal conditions. However, for air chambers on the envelope, the standard does not consider the exterior sheet to calculate transmittances. That is to say, it does not consider the resistance of the exterior plate. Anyhow, although the conductivity of the exterior plate's material is not significant for this calculation, it is a variable to be considered, given that the temperature inside the chamber can increase considerably compared to the external air. The IRAM 11600 series is the calculation basis of Standard 11900 (2017) of the Building Energy Certification, which is why the impacts on the envelope of the presence or absence of a ventilated envelope, be this on the façade or roof, are not considered when calculating the Energy Performance Index (IPE in Spanish). The results obtained in this research match those expressed by Fernández, Garzón and Elsinger (2020), who have shown that the thermal insulation increase strategies on the envelope, reduction of glazed surfaces and generation of crossed ventilation do not substantially affect the determination of the energy efficiency label of dwellings. As a result, it is possible to state that the ventilated construction systems are not being considered by the Argentinean regulation.

In consideration of these results, it is foreseen in the future to look further in the studies based on two aspects: on one hand, the evaluation of an effective rehabilitation in economic terms, that foresees integrating into the study, the analysis of materials available in Mendoza that can feasibly be adapted, like ventilated envelope, against the imported ventilated façade systems that can be bought into the country and into the region. And, on the other hand, regarding the regions with seismic risk, like the city of Mendoza, the joint assessment of this condition with the thermal rehabilitation is deemed essential (Manfredi & Masi, 2018). In this sense, the evaluation of the combined loads is considered, for the implementation of the exterior plates of the envelopes.

CONCLUSIONS

Building rehabilitation with energy efficiency criteria is essential in current urban contexts. The passive rehabilitation bioclimatic strategies, like the incorporation of thermal insulation and ventilated envelopes, appear as a valid and effective option in climates with high solar radiation.

The area evaluated for the thermo-energy rehabilitation of residential buildings – Central 2 area of Mendoza, has ten cases with possibilities for intervention on the north-facing facades. The audits made onsite in one of the cases that can be rehabilitated, along with their validation in the *EnergyPlus* model, allowed diagnosing considerable reductions in energy consumption in summer, given by the implementation of ventilation techniques on the envelope, like ventilated roofs and facades.

As for unoccupied buildings in the study, through the incorporation of ventilated envelopes on facades and roofs, important benefits were obtained compared to indoor thermal improvements, which represented energy savings of 32%, in comparison to the same building with insulation. Likewise, the ventilation on the roof implies important reductions in heat transfers, which led to energy reductions of 260% on the units located on the top floor with exposed roofs.

Starting from the study of building rehabilitation possibilities in the high density area of Mendoza, it is concluded that it is possible to achieve an effective thermal-energy performance through the integration of ventilated envelopes. The applicability of the methodology adopted requires monitoring and validation through the dynamic simulation of the indoor thermal performance of the building, through which it will be possible to predict improvements in the thermal-energy performance of existing dwellings, in high-rise, mid-rise and low-rise buildings.

ACKNOWLEDGMENTS

We would like to thank CONICET (National Scientific and Technical Research Council) for their financial support. We would also like to thank Cristina Pardal PhD and Ignacio Paricio PhD, from the Architectural Technology Department of the Polytechnic University of Catalonia, who guided the learning process of the envelope system being studied.

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