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VIVIENDA MARGARITA

Ubicada en la localidad de La Herrería (Fuente Palmera. Córdoba. España) la vivienda, se caracteriza por una arquitectura comprometida con el medio ambiente, reflejada tanto en el diseño como en las soluciones constructivas "ecoeficientes" adoptadas: fachada ventilada, forjado sanitario, ventilación e iluminación naturales, sistema de climatización hidrónico, placas solares fotovoltaicas para autoconsumo y un mortero fotocatalítico para el revestimiento interior y exterior que será capaz de descontaminar el aire que rodea a la vivienda y ofrecerá a su vez un acabado impecable, sin necesidad de mantenimiento periódicos. Se trata de un prototipo de vivienda *NZEB Nearly Zero Energy Building al amparo de un contrato art 68/86 L.O.U.* a través de la Fundación de Investigación de la Universidad de Sevilla. Este tipo de viviendasque apoyan la sostenibilidad regenerativa, minimizan el impacto ambiental derivado de un excesivo consumo energético y reducen las emisiones de CO_2 ala atmósfera, son hoy no solo una realidad, sino una tendencia general en el sector.

Estudio de Arquitectura R&M Arquitectos Asociados
Pilar Mercader Moyano,
Doctora Arquitecta. Profesora Titular Escuela Técnica Superior de Arquitectura Universidad de Sevilla (US). Directora del Master Propio Rehabilitación Ecoeficiente de Edificios y Barrios US. Presidenta del Congreso Internacional de Construcción Sostenible y Soluciones Ecoeficientes. Master en Patrimonio Histórico y Master en Peritación y Reparación de Edificios. Subdirectora de Calidad y Hábitat Sostenible E.T.S.A.
pmm@us.es
https://orcid.org/0000-0003-2180-4887

Daniel J. Ruesga Díaz,
Arquitecto Gerente R&M Arquitectos Asociados, Máster en Proyectos de Instalaciones en Arquitectura: Diseño, Cálculo y Eficiencia Energética, Técnico Superior en Prevención de Riesgos Laborales, Miembro de la Agrupación de Arquitectos y Peritos Forenses del Colegio Oficial de Arquitectos de Sevilla.
djruesga@gmail.com

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EDITORIAL

Me complace presentar la nueva edición de Revista Hábitat Sustentable V12N2, sostenida por la Facultad de Arquitectura Construcción y Diseño, cuyo valioso y nutrido repertorio de artículos colabora desde la investigación a la sustentabilidad en el ambiente construido, en distintas escalas. A través de significativos aportes a la discusión en ámbitos de la economía circular de recursos materiales y ciclo de vida de los edificios, resiliencia de ciudades y edificaciones frente al cambio climático, confort ambiental, habitabilidad, movilidad urbana y suficiencia lumínica, autores y autoras de Latinoamérica (Panamá, Colombia, Brasil, Bolivia, Argentina y Chile) comparten aquí sus propuestas.

Esta edición es un número especialmente emotivo ya que, después de ocho años a cargo de la Dirección y Edición de la Revista HS, es hora de cerrar este ciclo. Culmino esta valiosa labor, que ha estado plena de aprendizajes, desafíos e importantes logros para nuestra revista, acompañada de un excelente equipo de personas y profesionales con quienes logramos alcanzar indexaciones relevantes para HS, la cual hoy se encuentra en catálogos SCOPUS, SCiELO, ERIHPLUS, y WOS EMERGING SOURCES CITATION INDEX, entre otras.

Desde marzo del 2023, empieza una nueva etapa para HS que, sin duda, vendrá llena de éxitos y logros, de la mano de sus nuevos jefes Editores: Dra. Maureen Trebilcock, fundadora de la revista, y del Dr. Alexis Pérez; ambos destacados académicos e investigadores de la Facultad de Arquitectura, Construcción y Diseño, quienes, desde su experiencia y visión, continuarán consolidando la calidad de HS hasta posicionarla en las más altas indexaciones y visibilizaciones internacionales.

Por mi parte, quiero manifestar mis agradecimientos al valioso equipo humano que me acompañó profesionalmente en esta cruzada, en primer lugar, a la Ing. Jocelyn Vidal, encargada de la Coordinación Editorial, por su compromiso y disposición permanente al aprendizaje y la colaboración; a la Dra. Olga Ostria por su tremendo profesionalismo en el apoyo en la Corrección de Estilo, más en los intensos tiempos editoriales. Mismo reconocimiento para el Arq. Ignacio Sáez, por poner a disposición su talento y labores de diagramación en esos exigentes cierres, sobre todo los de fines de cada año. Mis agradecimientos también para Kevin Wright, por su impecable labor y compromiso en el apoyo de traducción de artículos; para Karina Leiva por el permanente apoyo en las tareas de soporte informático de la plataforma OJS y marcaciones de nuestros artículos, y para la a Arq. María Paz Cid, quien se sumó en el último periodo al equipo HS como apoyo editorial, por su colaboración y compromiso. Finalmente, y de manera muy especial, agradezco al Decano de la Facultad de Arquitectura, Arq. Roberto Burdiles, por su permanente apoyo a la Revista y a todo el equipo; apoyo que ha sido sustancial para conformar el equipo de Revistas FARCODI, ya sea facilitando el acceso a recursos como abriendo el espacio para la gestión e instalación del proyecto editorial de nuestra Facultad.

Por último, cierro esta columna deseándole el mejor de los éxitos a los nuevos jefes editores, al equipo que los acompañará en este nuevo periodo, esperando que HS continúe proyectándose y contribuyendo al conocimiento desde la investigación en ámbitos tan relevantes para las disciplinas del Diseño y Construcción del ambiente construido, de la mano de la sustentabilidad ambiental y social, dimensiones urgentes de abordar transversalmente.

Claudia Muñoz Sanguinetti
Doctora en Arquitectura y Urbanismo
Profesora Asociada Dpto. Ciencias de la construcción
Universidad del Bío-Bío, Concepción, Chile
https://orcid.org/0000-0002-4859-478X
clmunoz@ubiobio.cl

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DEVELOPMENT OF AN INTEGRATED SUSTAINABILITY AND STRUCTURAL SAFETY INDICATOR, APPLIED TO CENTRAL CHILE FOR THE WOODEN HOUSING MARKET[1]

DESARROLLO DE UN INDICADOR INTEGRADO DE SUSTENTABILIDAD Y SEGURIDAD ESTRUCTURAL PARA EL MERCADO DE VIVIENDAS DE MADERA APLICADO A CHILE CENTRAL

Rosemarie Garay-Moena
Magister en Ciencias e Industrias de la madera, Académica, Departamento de Desarrollo en Productos Forestales, Facultad de Ciencias Forestales y Conservación de la Naturaleza, Universidad de Chile. Santiago,Chile
https://orcid.org/0000-0002-7662-9724
rosemarie.garay@gmail.com

Miguel Castillo-Soto
Doctor en Recursos Naturales, Académico e Investigador, Laboratorio de Incendios Forestales, Facultad de Ciencias Forestales y Conservación de la Naturaleza, Universidad de Chile. Santiago, Chile
https://orcid.org/0000-0002-3880-9441
migcasti@uchile.cl

Consuelo Fritz-Fuentes
Doctora en Biomateriales Forestales, Académica, Departamento de Desarrollo en Productos Forestales, Facultad de Ciencias Forestales y Conservación de la Naturaleza, Universidad de Chile. Santiago, Chile
https://orcid.org/0000-0002-1803-620X
cfritz@uchile.cl

Carlos Hernández Ortega
Ingeniero Forestal, Titulado, Universidad de Chile. Santiago, Chile
https://orcid.org/0000-0002-1620-0846
carlos.hernandez.o@ug.uchile.

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RESUMEN

El mercado de viviendas en Chile, basado en madera, requiere una revisión complementaria en función de las ventajas competitivas que posee este material respecto a sus prestaciones técnicas y propiedades estructurales, para fortalecer el cumplimiento de la Ordenanza General de Urbanismo y Construcción [OGUC] chileno y los Códigos de Construcción Sustentables. En ese marco, el objetivo central de la presente investigación fue desarrollar un Indicador Integrado de Seguridad y Sustentabilidad (IISS) capaz de integrar aspectos normativos, sociales, territoriales y ambientales, conforme a las variables: (1) presentación, (2) sustentabilidad y (3) seguridad de una vivienda. Para esto, se recopiló información de 230 empresas constructoras en madera localizadas entre las regiones de Valparaíso y Los Ríos, en Chile Central; proceso en el que destacó la presentación del producto y la seguridad como insumos para aplicar la metodología de cálculo del IISS. Esta integración dio como resultado una clasificación de indicadores técnicos útiles para fomentar la utilización del material madera como opción constructiva que prevalezca o se complemente con otro tipo de materias primas.

Palabras clave
viviendas de madera, seguridad, sustentabilidad.

ABSTRACT

The wood-based housing market in Chile requires a complementary review that considers the competitive advantages of this material regarding its technical features and structural properties, to strengthen compliance with the Chilean General Urban Planning and Construction Ordinance (OGUC, in Spanish) and the Sustainable Building Codes. The purpose of this research was to develop an Integrated Sustainability and Safety Indicator (IISS, in Spanish), which integrates regulatory, social, territorial, and environmental aspects, considering (1) presentation, (2) sustainability, and (3) safety variables for wooden houses. For this, information was collected from 230 wood construction companies located between the regions of Valparaíso and Los Ríos, in Central Chile, where product presentation and safety were highlighted as inputs to calculate the IISS. This integration resulted in a classification of useful technical indicators to promote wood use as a construction option that prevails over or complements other building options.

Keywords
Wooden houses, Safety, Sustainability

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INTRODUCTION

Several studies (Domljan & Janković 2022, Soust-Verdague, Moya & Llatas, 2022, Harju, 2022; Luhas *et al.*, 2021; Andac, 2020; Toppinen, D'amato & Stern, 2020; Bugge, Hansen & Klitkou, 2016; Ollikainen, 2014; Cai & Aguilar, 2013; Cai & Aguilar, 2014) have emphasized that the consumption of forestry products is essential to improve and promote the quality of people's lives, sustainable development, and a transition towards biological-based circular economies. In this context, wood as a building material stands out with its sustainable properties (Viholainen *et al.*, 2021; Brusselaers, Verbeke, Mettepenningen & Buyesse, 2020), longevity in use (Luo, Mineo, Matsushita & Kanzaki, 2018), positive impact on the living environment (Harju, 2022; Rhee, 2018; De Morais & Pereira, 2015), aesthetic perception (Lähtinen *et al.*, 2021; Bhatta, Tiippana, Vahtikari, Hughes & Kyttä, 2017), carbon storage properties, and the reduction of greenhouse gas emissions (Lippke *et al.*, 2011; Petersen & Solberg, 2005).

From this approach, instruments are needed in Chile to objectively evaluate the wooden houses available on the market, and identify the advantages and disadvantages involved in building with this material, in compliance with mandatory and voluntary technical criteria. The problem identified in Chile is that the coherence of public and private bodies responsible for monitoring what is sold, and how offered wooden houses are installed, is unresolved since there are no tools for consumers to know what to look for when buying. This situation is related to factors such as the housing deficit (Fundación Vivienda, 2019; Vergara & Reyes, 2019), the shortage of supply, the applicability of subsidies linked to rising prices, and also the migratory effect. The purchase decision is mainly based on accessible prices and aesthetic visual attributes. In fact, there is a significant number of homes that are not being registered and revised. Added to this, there is a lack of information that consumers have access to before buying homes, regarding the technical benefits of wood.

In the Chilean regulatory area, according to the urban planning and construction law D.F.L. N°458 of 1976, wooden buildings, as well as those made of other materials, are obliged to build with systems registered and recognized by the Chilean Ministry of Housing and Urbanism. Compliance with these standards, as well as other voluntary ones found in sustainable building codes, including life-cycle analysis and carbon footprint measurements, is key to leading the productive sector towards higher habitability standards, where, until now, no background information quantifies the compliance of these provisions in the wood construction market (Castle, Garay, Tapia, Garfias & Orell, 2020).

The lack of standardization and availability of technical information is also supported by the shortage of products marketed under the Chilean Norm NCh1207 for the visual classification of radiata pine, a situation that was revised and ratified in the Chilean Scientific and Technological Development Fund (FONDEF, in Spanish) project, (IT16i10003), referring to critical infrastructure standards for homes located in urban-forest interface areas. There, the technical terms and conditions for the first design of an integrated system of safety and quality indicators for wood-based infrastructure were formulated, comparing Chilean and foreign standards based on the premise of establishing comparable conditions between one country and another (Castle *et al.*, 2020). From this experience, Garay, Pfenniger, Castle, and Fritz (2021a) submitted an IISS proposal to highlight the competitive advantages of wood construction elements and components, that is to say, emphasizing these on facing the demands the buyer market has so that they might be included by the supplier market to position wood as a reliable and standardized product.

In particular, the integrated safety and sustainability indicator (IISS) constitutes a value that is obtained by an analytical evaluation model applied to a product, considering the criteria that describe the competitive advantages of different construction typologies. As mentioned above, the IISS has been created for other wood products and published in previous research, including the Latin American Congress of Wood Structures (CLEM CIMAD 2019), and the Wood Conference Timber Engineering (WCTE 2021). Likewise, the IISS is an integrated indicator that allows evaluating technical, regulatory, social, and environmental aspects that condition sustainability and safety, in addition to the product presentation. In this way, importance is given to the quality and benefits of these elements for housing, while contributing for people to live in safe conditions.

The current analysis of the wood-based housing market indicates that the productive sector has the necessary potentialities to make progress with an offer that fits construction standards, due to advantages such as a low carbon footprint (compared to other materials), industrialization capacity, the adoption of domestic and international standards, and seismic, thermal,

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and acoustic efficiency. Measuring and revealing the technical attributes of wood allows for strengthening its weaknesses, for example, using wood preserved according to its exposure risk, giving protection against fire and biodegradation, as well as other threats linked to the location (Garay, Castle & Tapia, 2021b), which must be considered from the design, and evaluating each situation individually in advance. At the same time, there are pending tasks related to housing installation and commissioning considering the location, natural hazard conditions, and increased population demand. In this sense, many Chilean regulations currently state these aspects, but they do not have a legal weight that allows their inspection in the construction plans.

METHODOLOGY

The study material is a set of wooden houses based on the manufacturing processes of 230 companies from the field, located in the regions of Valparaíso, O'Higgins, Maule, Ñuble, Biobío, Araucanía, Los Ríos, and Metropolitan. The method consisted of the identification and cadaster of companies offering wooden homes on their web pages, which was followed by the creation of records on building typologies and their individual characterizations (based on the relevant information provided by the company for their product), classified under three criteria: (1) presentation (*Pt*); (2) sustainability (*St*); and (3) safety (*Sg*), which are explained and detailed in Figure 1A. The *Pt* attribute covers the product and company presentation, along with the services and after-sales of the product. This attribute is explained, given that companies must provide an after-sales service that leaves the consumer satisfied, and that is efficient in providing solutions for any issue. The *St* attribute is based on the construction standards and certifications that should be adopted, such as airtightness, carbon footprint, life cycle analysis, process quality, efficiency and innovation, and the acoustic and thermal characteristics of the wooden houses offered. Finally, the *Sg* attribute contemplates aspects regarding the durability of the houses and particularly their behavior when facing a fire, included in the OGUC. The information record incorporates and describes the presence or absence of this information for the houses offered, as well as their details and relevant explanations.

After completing the registration, the IISS values were determined for the different houses offered in the studied regions. In this way, the approach for the integrated indicator (IISS) was outlined, based on available regulatory information, and information from the registry. The analytical method of Saaty (2001), who suggests a sequence of calculations based on a combination of criteria that characterize the mathematical associativity between variables and their interrelationships, was used for this, giving, as a result, a consistency matrix, which contributes to the description of the dependent variable, in this case, IISS. This methodology is used based on the research published by Garay, Tapia, Castillo, Fernández & Vergara (2018); Garay *et al.* (2021a); Garay *et al.* (2021b); Garay, Pfenniger & Castillo (2021c).

The determination of the IISS began with the application of a Multicriteria Evaluation (MCE) or Analytical Hierarchy Method (AHP) proposed by Saaty (2001), which is used in the decision-making of multiple criteria and study variables to select a set of criteria based on different alternatives (Figure 1B). This methodology allows (1) identifying the parts of the system; (2) recognizing the weight of the system's parts; (3) identifying the links between parts; and (4) proposing a rational solution. It is also based on three principles: the construction of hierarchies, the establishment of priorities, and logic consistency. All this becomes necessary to avoid an arbitrary evaluation based on prejudices.

DEFINITION OF CRITERIA AND VARIABLES

The prompt definition of criteria and variables allowed identifying the attributes and their interactions following the layout found in Figure 1B. These attributes were determined as a result of onsite analysis and observations, as well as from the websites of companies that build wooden houses, and refer to the type of materials used, the market they cover, and the economic, social, and environmental context where these companies operate.

These criteria are structured in three main lines, that are detailed in Figure 1A: (1) Presentation; (2) Safety, and (3) Sustainability. Given that the IISS aims at encouraging the use of wood and highlighting the value of the structural advantages, and their techniques, it is of interest to evaluate the marketing strategies of the company and its after-sales service. Therefore, Presentation (*Pt*) seeks to identify the most relevant components reported to highlight the positive perception of wood to a successful customer acquisition; Safety (*Sg*) and Sustainability (*St*) were evaluated for the presence of the technical components declared, observed, or verified using the building rules of the OGUC and the sustainable building codes of the Chilean Ministry of Housing and Urbanism.

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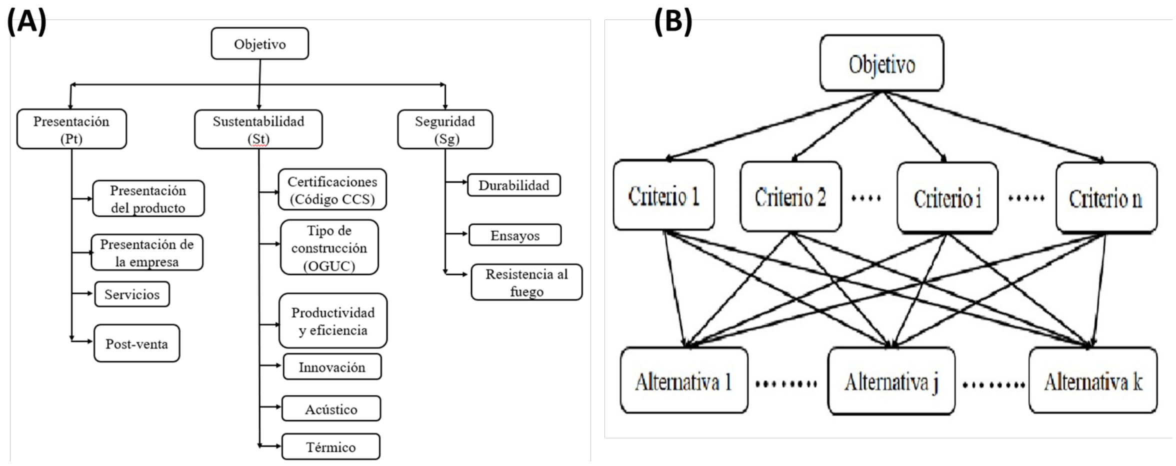

Figure 1. (A) Proposed layout of the Integrated Safety and Sustainability Indicator. (B) Standard model structure in the MCE methodology.
Source: Preparation by the authors using Saaty (2001).

1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Extreme		Strong			Moderate			The same			Moderate			Strong		Extreme
			Less important										More important			

Table 1. Priority setting scale.
Source: Preparation by the authors based on Saaty (2001).

n=3	Presentation (Pt)	Sustainability (St)	Safety (Sg)
Presentation (Pt)	1	$1/A_{21}$	$1/A_{31}$
Sustainability (St)	A_{21}	1	$1/A_{32}$
Safety (Sg)	A_{31}	A_{32}	1

Table 2. Example of a peer comparison matrix, where A_{21}, A_{31}, and A_{32} are the possible assigned scores and "n" is the number of variables.
Source: Source: Preparation by the authors based on Saaty (2001).

SCORE ASSIGNMENT

Following the method's second principle, each element is given a value based on a scale proposed by Saaty (Table 1), which reflects its weight, relative importance, or magnitude of preference. The assignment is made using a consensus at an average value designated by a panel of experts from the construction area (in this case 2 academics, 2 businessmen, and a government representative, all anonymous), who support the regulations and engineering related to the subject, provide ad hoc bibliography, and also review the analysis of the web pages of 230 companies in the sector.

The designation of these weights follows the peer comparison methodology of the same author, namely, where the importance of one factor compared to another is established. These were presented in a square matrix, with the number of rows and columns determined by the number of factors to be weighted, as shown in Table 2.

Then the *eigenvector* or *own vector* of the matrix is determined, which represents the order of priority of the factors. To do this, the values of the scores or weights established before are standardized, dividing each value of the comparison matrix by the total sum of the values of the column that corresponds to the value, as shown in equation 1, which results in what is expressed in Table 3.

$$N(Aij) = \frac{Aij}{\sum_{i=1}^{j=n} Aij} \qquad (1)$$

Where:
N(Aij) = Standardized value of the judgment in criteria matrix of row "i" in column "j".

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n=3	Factor 1	Factor 2	Factor 3	Peso Final
Factor 1	N(1)	N(1/A21)	N(1/A31)	$\sum N(A1i)/n = \beta 1$
Factor 2	N(A21)	N(1)	N(1/A32)	$\sum N(A2i)/n = \beta 2$
Factor 3	N(A31)	N(A32)	N(1)	$\sum N(A3i)/n = \beta 3$

Table 3. Standardized matrix. Source: Preparation by the authors

Matrix size (N)	2	3	4	5	6	7	8	9	10
Random index (Ri)	0	0,6	1	1,1	1,2	1,3	1,4	1,5	1,5

Table 4. Random consistency index value. Source: Preparation by the authors based on Saaty (2001).

Aij = Judgment value in the criteria matrix of row "i" in column "j".

Adding up the rows of the standards values yields the main *eigenvector*

$$\text{Eigenvector principal} = \sum_{i=1}^{j=n} N(Aij) \qquad (2)$$

The main *eigenvector* is standardized by dividing the result by the number of criteria in the matrix, which comes from the matrix of equation 2 (Saaty, 2001). The latter result is a percentage value that represents the weight value of each factor of the variables.

To confirm the validity of the assignment of scores or the relative importance of these final weights, the Consistency Ratio (Rc) is calculated, using equation 3.

$$(\mathbf{Rc} = \mathbf{Ic/Ri}) \qquad (3)$$

Where:
Rc: Consistency ratio (*Rc*),
Ic: Consistency Index (*Ic*),
Ri: Random index, a value contained in a table created at the Oak Ridge National Laboratory, which is characteristic for matrices from 1 to 15 (Table 4).

While *Ic* is a value obtained from equation 4:

$$Ic = (\lambda \max - n)/(n-1) \qquad (4)$$

Where:
n = number of factors of the matrix
$\lambda_{max.}$ = calculated from the sum of the resulting values of the result of the main eigenvector (β*1*, β*2*, and β*3*) with the score assignment matrix.

This is how, based on the methodology proposed by Saaty (2001) for values greater than or equal to 0.10, the value judgments must be reviewed, since they are not consistent enough to establish the weights.

To ensure the correct application of the AHP method, this combination must be done both at the level of criteria and variables within the criterion (level 1 and 2, respectively).

IISS CALCULATION

The IISS calculation consists of the sum of the result of percentage values (weights or relative importance) between the criteria (level 1) and their respective variables (level 2), and an additional assigned score from 1 to 5, where 1 represents the worst situation for the product evaluated, and 5, the best one. Each level is detailed and described in an evaluation spreadsheet.

IISS=C1*V1*P1+C1*V2*P2+…+C2*V1*P1+C2*V2*P2+…+C3*V1*P1+C3*V2*P2+… (5)

Where:
C_i: decimal or percentage value of the general criteria (*Pt*, *St*, and *Sg*)
V_i: Decimal or percentage value of the variable included in the general criterion.
P_i: Score assigned to the study variable, with 1 being low compliance and 5 being the one with the highest compliance.

From this model, the percentage value or relative importance of the variable alone within its respective criterion can be defined as a "local weight" (V_i in the model), and the result Ci x Vi as a "global weight", which accounts for its importance throughout the model.

Figure 2. Methodological sequence for IISS weighting and consistency evaluation. Source: Own preparation

Description	Intervals		
Low	1	-	2,33
Medium	2,33	-	3,67
High	3,67	-	5,00

Table 5. Characterization interval for the IISS.
Source: Preparation by the authors.

	Presentation	Safety	Sustainability
Presentation	1	2	3
Safety	0,5	1	2
Sustainability	0,33	0,5	1

Table 6. Cross-per matrix for the levels of the three criteria (Pt; Sg; St). Source: Preparation by the authors.

IISS WEIGHTING AND CONSISTENCY ASSESSMENT

At this stage, the following hierarchy was established, based on the information collected and analyzed from the 230 companies consulted:

Presentation (*Pt*); Safety (*Sg*); Sustainability (*St*)

The classification of the information provided by each company for their product is classified according to these three criteria, considering the importance with which these are presented and described through the internet as a means of dissemination and acquisition of goods and services, with suggestive power from visual stimuli, as well as learning power (de Lourdes, 2006). For this, the website must comply with different accessibility parameters (Varas, Agüero, Guzmán & Martínez, 2015), whose emphasis should be placed on identifying the most relevant components, including technological and technical compliance, and sustainability, which are part of the production chain. This method was used due to the difficulties of direct access caused by the COVID 19 pandemic.

Regarding the criterion associated with safety, the structural properties against earthquakes and fire are considered as most relevant, given the importance users give them, especially in the domestic context, that is prone to earthquakes and fires (Castle, *et al.*, 2020, Garay *et al.*, 2021a). In addition to this, companies, especially small ones (SMEs), still consider that sustainable construction implies an extra cost, which the client cannot pay (Fajardo, 2014; Hatt, Saelzer, Hempel & Gerber, 2012).

RESULTS AND DISCUSSION

APPLICATION OF THE INTEGRATED SAFETY AND SUSTAINABILITY INDICATOR (IISS)

Liss modeling, weighting, and consistency assessment

The modeling of the problem is represented in Figure 1, hierarchized from the first level of general criteria to the second level of variables that have been considered to determine the level of compliance of the products offered by companies.

The sequence of steps for the IISS calculation is presented in Figure 2.

	Product presentation	Company presentation	Services	After-sales service
Product presentation	1	0.5	2	3
Company presentation	2	1	3	5
Services	0.5	0.33	1	2
After-sales	0.33	0.2	0.5	1

Table 7. Cross-peer matrix for the variable levels of the Pt criterion. Source: Preparation by the authors.

	Certifications * (CCS, CEV)	Type of construction (OGUC, 5.3.1)	Productivity/ efficiency	Innovation (sustainable construction)	Acoustic comfort	Thermal conditioning
Certifications * (CCS, CEV)	1	0.20	0.25	0.33	0.5	0.5
Type of construction (OGUC, 5.3.1)	5	1	2	3	4	3
Productivity/efficiency	4	0.50	1	2	3	2
Innovation (sustainable construction)	3	0.33	0.5	1	0.5	0.5
Acoustic comfort	2	0.25	0.33	2	1	0.5
Thermal conditioning	2	0.33	0.5	2	2	1

Table 8. Cross-peer matrix for the variable levels of the St criterion. Source: Preparation by the authors.
*CCS: Sustainable Building Codes and/or CEV: Housing Energy Certification.

The characterization interval for the IISS is presented at three levels (Table 5) and the general criteria comparison matrix is prepared (Table 6)..

As indicated in the methodology, the procedure requires determining the Consistency Ratio, which yields a value of 0.9%, namely, high consistency in the assessment of the criteria, so the model is considered accepted.

The resulting IISS is compared in three cross-peer matrices (one for each criterion *Pt*, *Sg*, and *St*, explained in Tables 7, 8, and 9), considering the minimum to the maximum value that can be obtained, with the resulting IISS value classified as Low, Medium, or High (according to Table 5's ranges), depending on the compliance with the criteria, respectively (calculation examples in Figure 4).

The comparison matrix for *Pt* shows an Rc of 0.65%, namely, high consistency in the data assessment, so the model is accepted.

The Sustainability criterion (*St*) evaluates compliance with greater environmental commitment, where the information needs to be available, although potential customers cannot always afford the associated costs (Hatt *et al.*, 2012). There is interest in sustainability criteria, though they often end up giving greater purchase preference based on low costs, thus defining the following selection hierarchy: Type of construction > Productivity and efficiency > Efficiency > Thermal Cond. > Acoustic > Certification.

The comparison matrix for *St* shows an Rc of 4.2%, hence, high consistency in the data assessment, so the model is considered accepted.

Regarding the Safety criterion (*Sg*), and due to the recurrence of fires and the presumption of compliance with seismic resistance, fire protection regulatory parameters are privileged over the others. This is related to a social issue rooted in the population, regarding the fear of earthquakes and fires. For this

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Safety	Durability and treatment (OGUC, 5.6.8)	Tests (OGUC)	Fire resistance (OGUC, MINVU)
Durability and treatment (OGUC, 5.6.8)	1	2	0.50
Tests (OGUC)	0.50	1	0.33
Fire resistance (OGUC, MINVU)	2	3	1

Table 9. Cross-peer matrix for the variable levels of the Sg criterion. Source: Preparation by the authors.

Criterion	Weight	Variables	Local	Global	Score
Presentation	0.539	Product presentation	0.2718	0.1465	1 to 5
		Company presentation	0.4824	0.2600	1 to 5
		Services	0.1575	0.0849	1 to 5
		After-sales service	0.0883	0.0476	1 to 5
Sustainability	0.164	Certifications (transparency)	0.0667	0.0198	1 to 5
		Type of construction (OGUC, 5.3.1)	0.4000	0.1189	1 to 5
		Productivity/ efficiency process	0.2667	0.0793	1 to 5
		Innovation (sustainable construction)	0.0667	0.0198	1 to 5
		Acoustic	0.0667	0.0198	1 to 5
		Thermal conditioning	0.1333	0.0396	1 to 5
Safety	0.297	Durability and treatment (OGUC, 5.6.8)	0.2973	0.0487	1 to 5
		Testing (transparency)	0.1638	0.0268	1 to 5
		Fire resistance	0.5390	0.0883	1 to 5

Table 10. Local and global weights or weightings of criteria and variables. Source: Preparation by the authors.

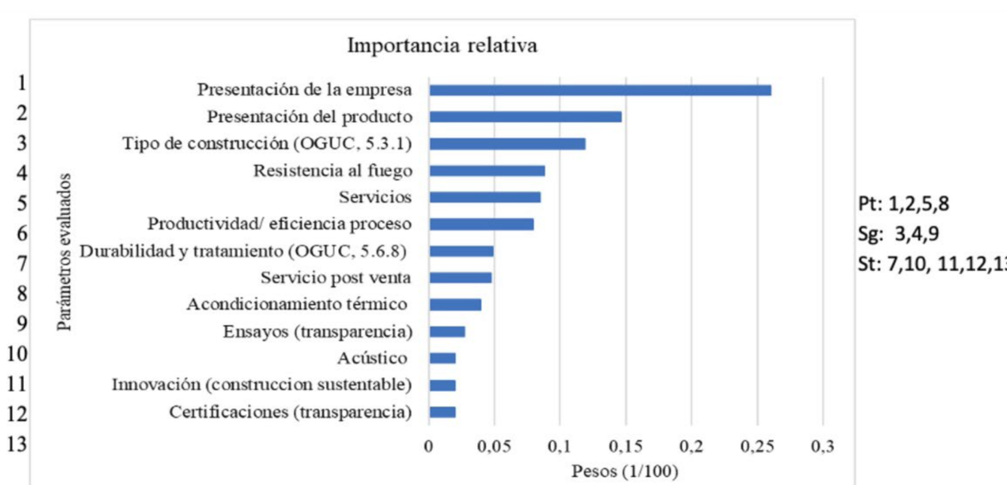

Figure 3. Evaluation of relative importance of parameters. Source: Preparation by the authors.

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A) Ejemplo de cálculo IISS, valorización "ALTA"

Empresa	Imagen producto	Descripción	Otras Observaciones
Construkit		Casa Base, modalidad prefabricado	Se destaca por la publicidad de los tratamientos e innovación del proceso: eficiencia

Criterio	Variable	Ptaje	Peso global	Producto
Presentacion	Presentación del producto	3	0,146	0,44
	Presentación de la empresa	4	0,260	1,04
	Servicios	3	0,085	0,25
	Servicio post venta	2	0,048	0,10
Sustentabilidad	Certifiaciones (Código CCS)	3	0,020	0,06
	Tipo de construcción (OGUC, 5.3.1)	5	0,119	0,59
	Productividad/ eficiencia proceso	5	0,079	0,40
	Innovación (construccion sustentable)	5	0,020	0,10
	Acústico	4	0,020	0,08
	Acondicionamiento termico	4	0,040	0,16
Seguridad	Durabilidad y tratamiento (OGUC, 5.6.8)	4	0,049	0,19
	Ensayos (transparencia)	4	0,027	0,11
	Resistencia al fuego	3	0,088	0,26
	SUMA	49	1	3,78

B) Ejemplo de cálculo IISS, valorización "MEDIA"

Empresa	Imagen producto	Descripción	Otras Observaciones
Construkit		Modalidad industrializada, panel SIP	Empresa se destaca los tratamientos empleados a las piezas que utiliza

Criterio	Variable	Ptaje	Peso global	Producto
Presentacion	Presentación del producto	4	0,146	0,586
	Presentación de la empresa	3	0,260	0,780
	Servicios	2	0,085	0,170
	Servicio post venta	2	0,048	0,095
Sustentabilidad	Certifiaciones (Código CCS)	2	0,020	0,020
	Tipo de construcción (OGUC, 5.3.1)	1	0,119	0,119
	Productividad/ eficiencia proceso	5	0,079	0,079
	Innovación (construccion sustentable)	2	0,020	0,020
	Acústico	2	0,020	0,020
	Acondicionamiento termico	2	0,040	0,040
Seguridad	Durabilidad y tratamiento (OGUC, 5.6.8)	4	0,049	0,049
	Ensayos (transparencia)	2	0,027	0,027
	Resistencia al fuego	3	0,088	0,088
	SUMA	34	1	2,09

C) Ejemplo de cálculo IISS, valorización "BAJA"

Empresa	Imagen producto	Descripción	Otras Observaciones
Casas Entrelagos		Vivienda prefabricada, formato kit completo	Sin observación

Criterio	Variable	Ptaje	Peso global	Producto
Presentacion	Presentación del producto	2	0,146	0,29
	Presentación de la empresa	2	0,260	0,52
	Servicios	3	0,085	0,25
	Servicio post venta	2	0,048	0,10
Sustentabilidad	Certifiaciones (Código CCS)	1	0,020	0,02
	Tipo de construcción (OGUC, 5.3.1)	3	0,119	0,36
	Productividad/ eficiencia proceso	3	0,079	0,24
	Innovación (construccion sustentable)	4	0,020	0,08
	Acústico	1	0,020	0,02
	Acondicionamiento termico	3	0,040	0,12
Seguridad	Durabilidad y tratamiento (OGUC, 5.6.8)	3	0,049	0,15
	Ensayos (transparencia)	1	0,027	0,03
	Resistencia al fuego	1	0,088	0,09
	SUMA	29	1,000	2,26

Figure 4. Examples of IISS calculation by type of valorization: (A) "High"; (B) "Average", and (C) "Low" levels. Source: Preparation by the authors.

reason, the following selection hierarchy is established: Fire resistance > Durability and treatment > Tests

The comparison matrix for *Sg* yields an Rc of 1%, high consistency in the data assessment, therefore, the model is accepted.

Finally, the local and global weights are presented in Table 10.

The relative importance of the evaluated parameters reflects the order of priorities under which the various corrective actions must be focused on. This is how, from the assignment of weights to obtaining the global and local weights, it was obtained that the parameters of "project presentation", "type of construction", and the actions regarding Fire Resistance had greater relative importance in the study (Figure 3).

Company	Product picture	Description	Pt	St	Sg	Other Observations	IISS	value
Construkit		Basic house, prefabricated	1.829	1.387	0.567	This stands out by advertising the treatments and innovation of the process: efficiency.	3.78	High
Casas Calera de Tango		Turnkey housing, prefabricated	2.175	1.030	0.465	This stands out through a scaling process, offering from a basic kit to a turnkey modality.	3.67	High

Table 11. IISS application, example of "High" value indicator. Source: Preparation of the authors based on the information provided by the evaluated companies.

Company	Image	Description	Pt	St	Sg	Other Observations	IISS	value
Constructora ROKAR		Traditional house	1.886	0.971	0.340	Good presentation. A more detailed description of housing materials is missing. Lacks detail or innovations, or types of certificate.	3.20	Average
		Modular	1.886	1.09	0.340		3.32	Average
Easywood		Industrialized, SIP panel	1.716	1.209	0.513	The company stands out for the treatments used for the pieces it uses.	3.44	Average
Fundación vivienda		Single slope, prefabricated	1.796	0.595	0.164	This stands out through the presentation of the company, but not its products.	2.55	Average
Decocasas		Not specified	1.210	1.030	0.164	This stands out through its sustainability and design or use of its materials to generate acoustic and thermal comfort.	2.40	Average

Table 12. IISS application, example of "Average" value indicator. Source: Preparation of the authors based on the information provided by the evaluated companies.

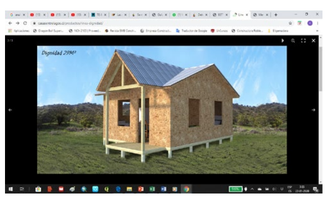
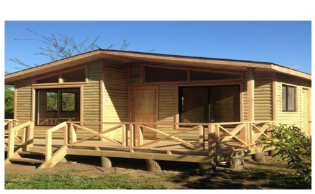
Company	Image	Description	Pt	Sg	St	Other Observations	IISS	value
Constructora ARQOS		Rustic model	1.51	0.54	0.16	Fire risk due to fuel overload.	2.21	Low
Casas Interlagos		Prefabricated, complete kit format	1.16	0.83	0.26	No comments.	2.26	Low
Constructora Rinconada Ltda.		Prefabricated, SIP, and SmartPanel	0.90	0.97	0.16	It does not have its own website; it is associated with a Ministry page (SERVIU).	2.04	Low
Constructora ROA	No sample picture	Associated with commercial page	0.76	0.63	0.16	Associated with commercial page.	1.55	Low
Casas Rucaray		Builder	1.33	0.71	0.26	Facebook page only.	2.31	Low

Table 13. IISS application, example of "Low" value indicator. Source: Preparation of the authors based on the information provided by the evaluated companies.

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GENERATION OF THE INTEGRATED SAFETY AND SUSTAINABILITY INDICATOR (IISS)

Once the presented methodological steps have been completed, it is possible to present the resulting model, which can be applied in the evaluation of dwellings published on web pages of wood construction companies, and then onsite observations. Figure 4 shows examples of how the IISS calculation methodology was applied from a valuation classified as "high", "average" and "low", as appropriate.

IISS APPLICATION

To apply the model, the most representative situations inspected (230 companies from their websites) were considered, which are summarized in Tables 11, 12, and 13.

Examples of dwelling typologies are presented in the tables above, describing those with a "High" assessment indicator (Table 11), which is explained mainly by these having high scores on the *Pt* criterion, superior in this category to companies with the "Average" indicator, and highlighted in Sustainability (*St*) thanks to certain aspects informed as energy-saving materials (double-glazed windows) and the use of certain innovations (wood stabilizers).

Those types who obtained a high value on the *Pt* criterion (Table 12) were classified with the "Average" indicator. This assessment highlighted meaningful attributes of the company (over a product description), such as background, sales system, and annual reports with production details, among others. There is less clarity in sustainability and safety compared to the previous group, as the environmental virtues of the wood they use were declared, but not the participation of any type of certification that would endorse them. While some companies are stronger in declaring sustainability, others are stronger in declaring safety, when working with treated wood or designing reinforced structures with high regulatory compliance.

The reasons why some companies, responsible for the information they provide about their products, had a "Low" indicator (Table 13) can be summarized in the following three points: 1) They do not have their own web page and are referenced by other sources; only provided identification and contact information: phone or e-mail; 2) They are associated with an institutional page or only use social media such as Facebook, standing out for giving price information, minimum technical specifications, and product image; and 3) They have a basic website, equivalent to an online blog, with a gallery of images of their projects, without verification of technical or design conditions; they only present contact details.

The application of the IISS is of great importance because it can be implemented to cover needs that are being incorporated in other countries, such as the impacts of disasters and the safety of the houses and their users (Castillo *et al.,* 2020), for which it is required to find agreements and improve coverage from insurance companies.

In addition, insuring a home could lead to the development of a maintenance culture, charged to that insurance so that the installations function properly, and so that the durability and resilience of houses to natural events increases. Also, if the living conditions are adequate, the health risks of present and future users would be reduced. From the economic point of view, it can be mentioned that properly made inspections can increase the purchase value by up to 40%, so banks would be more inclined to give loans (Dolan, 2018).

Finally, well-insured houses are also a marketing strategy that can be complemented with the promotion of the attributes of a wooden home, which could persuade the public to opt for this type of structure.

The wood construction sector is making great strides. Rapid and correct measures will allow its inclusion in the sustainable building market, namely, through the progressive adoption of sustainable building codes.

The analysis presented here has implications for the requirements to be implemented to install homes in forest fire areas, similar to the strategies of Australia, Canada, and the United States, where the regulations consider demands by location, exposure, and risk. In Chile, there is a lack of progress in inspection for the installation and insurance of housing, although progress should be acknowledged in the area of hospitals and high-rise buildings, where the inclusion of LEED or Passive house certifications has made it possible to incorporate higher demands. Unfortunately, these advances have not reached the most common houses, such as those of all Chileans.

Faced with disaster situations, experts propose that the building code should be on a par with on-site inspection actions, as is the case in countries such as the United States, Japan, and New Zealand, where laws support inspections at the beginning, during, and end of the work and whose associated costs are part of construction permits, which represent 0.5% or less of the total work (Dolan, 2018).

Linking the IISS to these inspections can be another benefit since by making sure that the installations are done properly, the durability and resilience of houses to events that trigger disasters and facilitate purchase-sale and insurance companies relations increase. In the same vein, if the habitability conditions are adequate, the risks to user-health are reduced.

For all these reasons and more, it can be argued that the wood construction sector is heading in the right direction, so measures must be adopted quickly so that this material and all those who work with it are included in these processes. Materials and trained professionals are available; just collaboration, inclusion, and technical advice are required.

CONCLUSION

The integration of presentation, sustainability, and safety criteria to generate a combined IISS indicator for wooden houses manufactured in central Chile, allows assessing the technical, structural, and applicability aspects of wooden housing, as a highly competitive construction product, in a growing and increasingly diverse market context.

As a result, the degree of importance of different variables and their technical coefficients (expressed in rankings and prioritization between wood-based constructive choices) made it possible to obtain a hierarchical order or ranking of wood material use options under the current regulatory and installation restrictions, and after-sale processes, under normal operating conditions for habitable territories in Central Chile.

The IISS is a contribution to housing assessment and would have greater significance if it were complemented with an onsite evaluation, to verify other factors and contribute to improving the productive chain by reaching an agreement about strategies.

The results allow ranking the products of companies that manufacture wooden houses according to the three attributes needed, so consumers can buy in an informed way, and not just be led by the aesthetic characteristics of the houses. Due to the lack of technical quality and clarity of information regarding compliance with the OGUC, sustainability codes and/or sustainable housing certifications (CVS) have not yet been adopted by the Chilean market. The application of this indicator can contribute to categorizing available housing, where consumers may find themselves faced with purchase decisions where issues such as preservation treatments, thermal insulation, fire protection, standardized construction systems, and process sustainability are valued and quantified, both by the customer and the manufacturer.

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VALIDATION OF PROPOSALS FOR THE ENVIRONMENTAL OPTIMIZATION OF A COMPACT-TYPOLOGY KINDERGARTEN, IN A VERY HOT-HUMID CLIMATE[1]

VALIDACIÓN DE PROPUESTAS DE OPTIMIZACIÓN AMBIENTAL DE UN JARDÍN DE INFANTES DE TIPOLOGÍA COMPACTA, EN CLIMA MUY CÁLIDO-HÚMEDO

María Laura Boutet
Doctora en Ciencias Área Energías Renovables, Investigadora Asistente, Docente-Investigadora Categoría III (SPU), Instituto de Investigación para el Desarrollo Territorial y del Hábitat Humano (IIDTHH) - Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Facultad de Arquitectura y Urbanismo, Universidad Nacional del Nordeste (UNNE). Resistencia, Argentina
https://orcid.org/0000-0001-6313-9577
arq.mlboutet@gmail.com

Alejandro Luis Hernández
Doctor en Ciencias Área Energías Renovables, Profesor Asociado e Investigador Independiente, Docente-Investigador Categoría I (SPU), Director del Instituto de Investigaciones en Energía No Convencional (INENCO) - Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Universidad Nacional de Salta (UNSa). Salta, Argentina
https://orcid.org/0000-0001-9808-3972
alejoher65@gmail.com

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RESUMEN

El siguiente artículo presenta el procedimiento de validación de propuestas de optimización de un prototipo de jardín de infantes de tipología compacta, según pautas de diseño bioclimáticas pasivas, mediante modelos físicos de simulación dinámica calibrados con mediciones *in situ*. El objetivo es verificar los parámetros de área vidriada (Av), absortancia solar promedio ponderada ($\bar{\alpha}$) y área de envolvente total ($A_{envolvente}$) utilizados como datos de entrada para la obtención de correlaciones de Factores de vidriado (Fv), en una herramienta de estimación de áreas vidriadas óptimas orientada a integrar el confort térmico y visual en el diseño de espacios educativos, en el clima Muy Cálido Húmedo de la Región Nordeste Argentina. Como resultado, se obtuvo una reducción de los requerimientos de refrigeración de hasta el 72% en el mes de noviembre, más desfavorable para la actividad escolar, al bajar la absortancia solar de las superficies exteriores a 0.25, con una relación de área vidriada por área de piso de 17% que posibilitó notables mejoras en la distribución espacial de la luz natural, recurso fundamental para el desarrollo integral de los niños del Nivel Inicial.

Palabras clave
energía solar, arquitectura escolar, confort térmico, confort lumínico.

ABSTRACT

This article presents the validation procedure of optimization proposals for a compact-typology kindergarten prototype, following passive bioclimatic design guidelines, using dynamic simulation physical models calibrated with onsite measurements. The objective is to verify the parameters for the glazed area (gA), weighted average solar absorptance ($\boldsymbol{\alpha}$), and total envelope area (envelopeA), using them as input data to obtain correlations of glazing Factors (gF) into a tool to estimate optimal glazed areas, aiming at integrating thermal and visual comfort in the design of educational spaces, in the Very Hot-Humid climate of the Argentine Northeast. As a result, a reduction of up to 72% was obtained in November, the most unfavorable month for school activities, for cooling requirements, by lowering the solar absorptance of exterior surfaces to 0.25, with a glazed area per floor area ratio of 17%, which made noteworthy improvements possible in the spatial daylight distribution, a key resource for the comprehensive development of children from Initial Schooling Levels.

Keywords
Solar energy, School architecture, Thermal comfort, Light comfort

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INTRODUCTION

Several international studies show the direct relationship between classroom indoor environment quality and student learning. In fact, temperature plays a primary role in academic performance (Muñoz, 2018), as does daylighting, which is particularly important for children's physical, cognitive, and emotional development, as they are even more sensitive to its dynamic effects (Montessori, 1998, Chilean Energy Efficiency Agency [Achee, in Spanish], 2012; Yacan, 2014; Monteoliva, Korzeniowski, Ison, Santillan & Pattini, 2016, Pagliero Caro & Piderit Moreno, 2017, Extremeña Energy Agency [AGENEX, in Spanish], 2020).

However, finding the balance between hygrothermal and light living conditions in regions with harsh climates is not an easy goal to achieve using passive design strategies, even more so in the context of global climate change, whose extreme weather events are becoming more frequent (IPCC, 2019). In these areas, ensuring optimal indoor conditions has a direct environmental impact on energy consumption levels and their consequent CO_2 emissions to the atmosphere (Baserga, 2020). In addition, the epidemiological situation generated by the Covid-19 pandemic, where sunlight, daylighting, ventilation, and social distancing (Cistern and Abate, 2021) have become key in the use of educational infrastructure, has highlighted the need for new comprehensive approaches, models and solutions.

In this vein, numerous research projects (Trebilcock, Soto, Figueroa & Piderit, 2016; Souza, Nogueira, Lima & Leder, 2020; Coronado, Stevenson-Rodriguez & Medina, 2021; Lamberti, Salvadori, Leccese, Fantozzi & Bluyssen, 2021; Rupp, Vásquez & Lamberts, 2015) have questioned the use of conventional comfort standard in schools, as they were developed based on adult subjects whose comfort perceptions and preferences may differ from those of children in various stages of development, demonstrating the need for a local view in Latin American, not just from the aspects of energy-saving and operational costs, but mainly regarding physiological, psychological, social, and cultural variables. However, the evaluation of thermal comfort in kindergartens is a recent topic and only a few works can be found in the specialized literature (Lamberti *et al.*, 2021: Yun *et al.*, 2014; Fabbri, 2013; Nam, Yang, Lee, Park & Sohn, 2015, Zomorodian, Tahsildoost & Hafezi, 2016). Also, there are no metrics to evaluate the daylighting intended exclusively for kindergartens or children's spaces.

One of the passive design variables of educational buildings, which has been and is widely studied for its impact on both energy performance and integrated environmental comfort, is the optimal layout of glazed areas considering the envelope area exposed to solar radiation. This also includes the effects of random variation in the occupation (Ochoa, Aries, van Loenen & Hensen, 2012; Lartigue, Lasternas & Loftness, 2014; San Juan, 2014; Futrell, Ozelkan & Brentrup, 2015; Mangkuto, Rohmah & Asri, 2016; Capeluto, 2019; Chiesa *et al.*, 2019; Filippín, Flores Larsen & Marek, 2020; Ré & Bianchi, 2020).

In the work of Ochoa *et al.* (2012), discrete variations of the window-wall ratio were studied, and it was concluded that most of the project expectations can be met within a variety of sizes, provided they have additional control devices. Lartigue *et al.* (2014), as well as Futrell *et al.* (2015), also considered the window type characterized by its visual and thermal properties, observing that, depending on the orientation, the thermal and daylighting objectives may clash greatly. Alwetaishi (2019) analyzed the impact of modifying the window-wall ratio in different climatic zones of Saudi Arabia, recommending 10% in hot and dry climates, as well as hot and humid ones, and 20% in moderate climates. Pérez and Capeluto (2009), on the other hand, tested a base case in the warm–humid climatic zone using computer simulation, and recommended, for north and south-facing windows, 12% of the classroom floor area. For west and east-facing areas, it is preferable to reduce the window size to 10% of the floor area, with dynamic shading devices to avoid glare due to lower solar angles. Not only the window size, but also its orientation, have a great effect on internal conditions, being the main aspect responsible for determining the degree of sun exposure and, therefore, direct heat gain (Gasparella, Pernigotto, Cappelletti, Romagnoni & Baggio, 2011, cit. in Alwetaishi, Alzaed, Sonetti, Shrahily & Jalil, 2018).

Considering the problem, an analysis of a particular case of the city of Resistencia, Chaco province, in the Northeast Region of Argentina (NEA, in Spanish) is presented, characterized by very hot-humid weather to check, by simulation, the relevance of the glazed areas proposed as optimal regarding different design variables of its constructive envelope. The original contribution of this work lies in the procedure for evaluating thermal and lighting issues simultaneously, whose objective is to validate a tool for estimating glazed areas by orientation, developed for school typologies of the NEA region and that can be extrapolated to other geographical regions with a hot - humid climate.

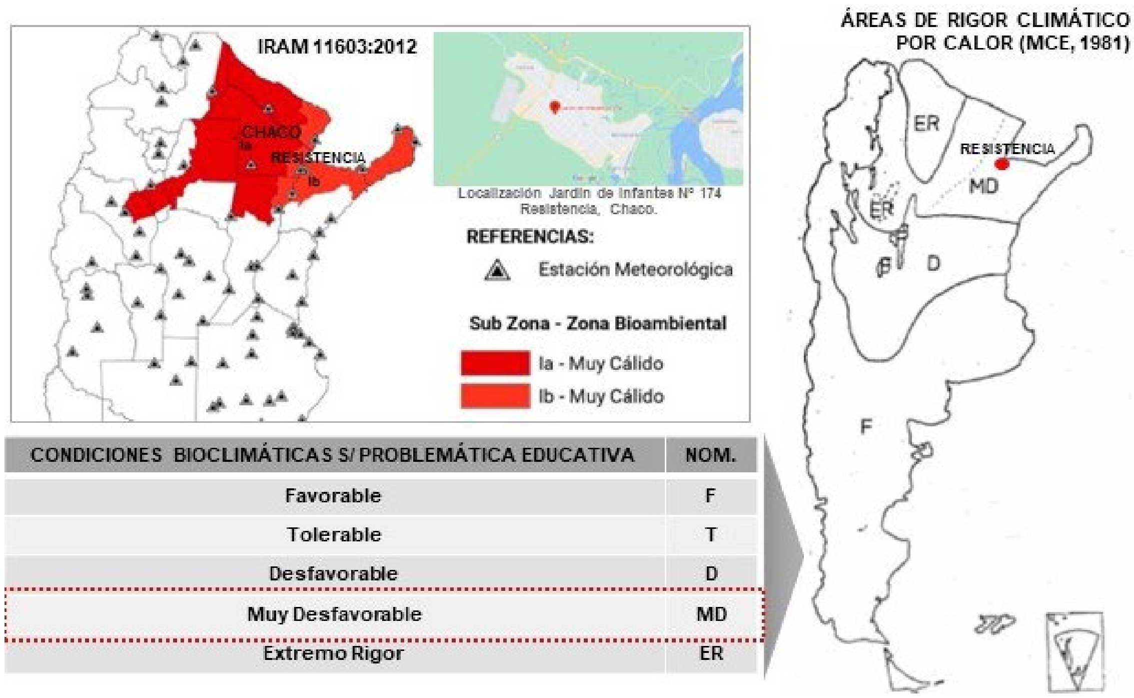

Figure 1. Location of the study area. Source: Preparation by the authors based on bioenvironmental classification maps using IRAM 11603:2012 and MCE (1981).

METHODOLOGY

BACKGROUND

According to the Argentine bioclimatic zoning (Figure 1), considering the influence of climate on educational problems (Ministry of Culture and Education [MCE, in Spanish], 1981), Resistencia (27.45° Lat. South; 59.05° Long. West; Alt. 52 masl) is located in a "Very Unfavorable due to Heat" bioclimatic zone, presenting 6 to 8 months, which cover a large part of the school period, with an average maximum temperature equal to or greater than 28°C, and with the influence of humidity that exacerbates the feeling of discomfort due to heat. This region corresponds to the Bioenvironmental Zone Ib "Very Hot and Humid" climate, according to IRAM 11603 (2012), and is characterized by thermal amplitudes of less than 14°C, maximum temperatures above 34°C, and an average daily global solar irradiation of 5.5 kWh/m^2 in November (the last full month of the common school period), with an average effective heliophany of 8 hours (Grossi Gallegos & Righini, 2007).

Associated with this, the urban sector of Resistencia is located at mid-orientation (45° with respect to the true North), so the glazed areas of the buildings receive solar radiation in all seasons of the year. These are actually areas that are blocked with curtains or other devices that prevent optimal use of daylight. The current regulations (General Building Regulations, 1990; National Ministry of Education and Culture [MCEN, in Spanish], 1996) do not comprehensively consider the climate and location features of Resistencia, so the design decisions, regarding the determination of lighting and ventilation openings, are subordinate to percentage values by floor area, uniform for each orientation, and without consideration of the morphology, degree of exposure, and the materialization of the envelope of buildings, nor their occupation system.

In response to the issues raised in a previous study, Boutet & Hernández (2020) developed a tool for Estimating the Glazing Factor (gF) using Multivariate Linear Regression (MLR), to calculate the optimal glazed areas of open (with two lighting and ventilation fronts; greater exposed envelope surface) and compact (with a single front) typology school buildings of the different educational levels (preschool, primary, secondary, and high school). The Glazing Factor, *gF* (dependent variable), is a new parameter defined by the authors that allowed connecting the (independent) variables considered as most significant by orientation, given their incidence on thermal balance: weighted average solar absorbance () of the opaque exterior surfaces, considering their finishing color (implies the fraction of incident solar radiation that is absorbed by the envelope materials); glazed area of doors and windows (gA); and the total opaque and glazed envelope area ($_{envelope}A$). This relationship is expressed in the following equation [Eq. (1)]:

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$$F_v = \frac{\bar{\alpha}.A_v}{A_{exp}} \qquad (1)$$

Where, *Fv*: Glazing Factor of each room by orientation; : weighted average solar absorbance of all exterior surfaces; $_{g}A$: total area of glass in windows and doors exposed to the outside; $_{exp}A$: area of facades and roofs exposed to the outside, discounting *gA*. Then $_{exp}A = {}_{envelope}A - {}_{g}A$.

From this factor, the equation to calculate the optimal glazed area is cleared, where an inversely proportional relationship with the solar absorbance is verified [Eq. (2)]. The higher the absorbance value (darker surface), the smaller the admissible glass area.

$$A_v = \left(\frac{F_v}{F_v+\bar{\alpha}}\right) A_{envolvente} \qquad (2)$$

Based on this new factor and its determination in a Generic Optimization Proposal, it was possible to formulate the proposed tool, which is the result of a statistical analysis of dynamic simulations calibrated with annual measurements of the hygrothermal and light behavior of 8 school buildings of different educational levels, selected because of their high sun exposure. The Generic Proposal verified the necessary habitability conditions, with the consequent reduction of air conditioning loads by between 40 and 60% on average (Boutet & Hernández, 2021).

Based on this information, in this work, it was proposed to make a review of the input data used to obtain correlations of Glazing Factors (*Fv*) of the initial level compact typology (Kindergarten N° 174), selected among the 8 buildings monitored at the time. To do this, the relevance of the glazed areas proposed for different solar absorption values was verified by simulation, in the month of November, as this is the most unfavorable school season (warm atmosphere, solar gain through the windows, and higher level of activity), which entails overheating situations. The aforementioned revision makes it possible to make a preliminary validation of the Glazing Factor (*Fv*) estimation methodology, which leads to new analysis situations that, in short, statistically reinforce its formulation.

VALIDATION PROCEDURE

The validation procedure using dynamic simulation consisted of the following methodological steps, presented in the flow diagram of Figure 2:

a. **Review of energy audits,** carried out during the period from November 12th to November 19th, 2012 in Kindergarten No. 174 using HOBO MOD U12-012 (T°C/%RH/Lx) data acquirers. and an ONSET (USA) H21-002 Microstation that was installed in the urban area where the building is located, to obtain accurate microclimatic conditions. This activity involved complementary objective observations, surveys of teachers and authorities, and daily recording of user behavior patterns.

b. **Validation of physical models.** With the measurements, the hourly temperature data obtained by SIMEDIF *V2.0* (Flores Larsen, 2019) and the illuminance data obtained by exporting

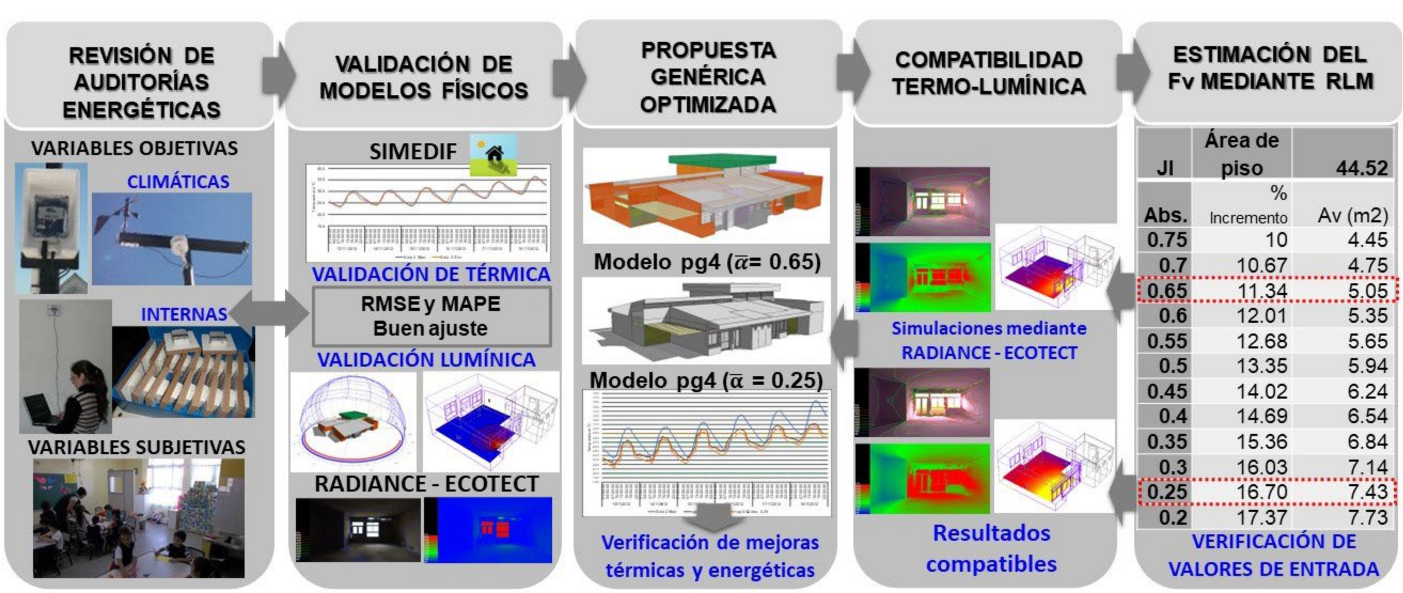

Figure 2. Methodological steps. Source: Preparation by the authors.

them to the RADIANCE interface of Autodesk Ecotect Analysis, were validated. Two indices were used: the Root Mean Square Error or RMSE [Eq. (3)], which quantifies the magnitude of deviation between the measured and simulated values in terms of units of variables by the square root of the mean square error, and the Mean Absolute Percentage Error or MAPE [Eq. (4)] performance indicator, that measures the size of the relative error as percentages (%).

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}[(x_{med})_i - (x_{sim})_i]^2}{N}} \quad (3)$$

$$\mathrm{MAPE} = \frac{\sum_{i=1}^{n} \frac{|x_{med} - x_{sim}|}{|x_{med}|}}{N} \quad (4)$$

Where, Xmed : measured values; -Xsim: simulated values; and N- number of measurements.

c. **Optimized Generic Proposal.** The obtained models were used to simulate the thermal and light behavior of the prototype, in the same period of November, applying the Optimized Generic Proposal (Boutet & Hernández, 2021) for different solar absorbance values of the exterior surfaces (α= 0.65 and 0.25). The reduction percentage of cooling loads was also verified, through simulations with thermostatization in Simedif, setting a temperature of 25°C. This value is the comfort temperature recorded from the monitoring and at which the air conditioning equipment in schools is usually regulated.

d. **Thermo-light compatibility.** The average illuminance totals (lx) calculated using Radiance - Ecotect, were compared with the corresponding temperature obtained by Simedif, at three times (9 am, 1 pm, and 4 pm) on the sunniest day, to verify whether thermal well-being is compatible with adequate daylight, considering the local comfort ranges established. A winter thermal comfort zone of 20 to 25°C and a summer comfort zone of 25 to 29°C are considered reference values at a regional level but for the statistical analysis, based on the regional limit values and the representativeness of the variables measured throughout the monitoring year, an average temperature range of 20 to 27°C and of 35% to 65% RH was defined, values that are also consistent with international standards (Boutet, Hernández & Jacobo 2020). For the illuminance analysis, the range of 300 to 500 lx (up to a maximum of 750 lx), recommended by IRAM AADL J-2004 (1974) and MCEN (1996) Standards, was considered.

Estimation of *Fv* by Multivariate Linear Regression. The verification of the relevance of the input data of the Glazing Factor (*gF*) estimation tool, for the Compact Kindergarten Typology, is concluded, highlighting its implications and the importance of the findings obtained.

DESCRIPTION OF THE CASE STUDY

Kindergarten No. 174 is a representative prototype of the official school architecture used in the province of Chaco, through the More Schools National Program. It is located in the San Miguel de Resistencia neighborhood, a residential area with low building density. It was opened in 2010, with a total covered surface area of 573 m². It is a compact typology building with 4 symmetrical classroom modules of 49 m² each, integrated into pairs by sliding panels, including semi-closed SUM. It has exposed surfaces towards the 4 middle orientations, without external solar barriers (Figure 3). It is characterized by its traditional technology, which is described in Table 1.

Figure. 3. Location of Kindergarten No. 174 and photo of its main entrance. Source: Preparation by the authors.

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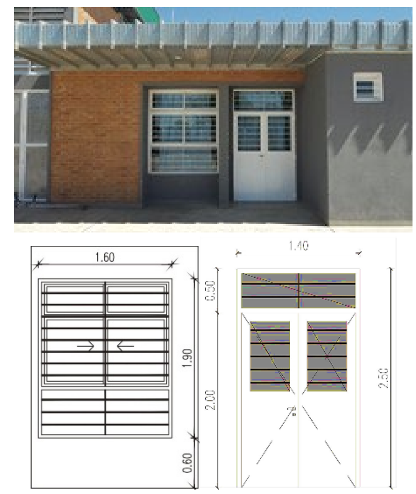
Walls	Masonry comprising 0.20 thick reinforced common load-bearing bricks, visible on the outside and coated inside	
Roofs	Ventilated self-supporting sheets (aerators every 2m) on a metal structure with glass wool insulation with aluminum foil.	
Ceilings	Plaster sheets on the inside or applied under the slabs of galleries and services	
Floors	30 x 30 cm granite mosaics inside and in galleries and 15 x 15 cm in wet areas	
Openings	Each classroom has 3 1.60 x 1.90 m openings of double glazed frames N°16 and aluminum sheets with 3+3 mm laminated glazing, located one towards the outside and two towards the non-exposed interior, formed by sliding and fixed panels. The doors have a fixed upper panel and two folding sheets, with 3+3 mm laminated glass.	
Protections	Security bars and roof eaves. Internal curtains on doors and windows. Sunshades of different sizes with fixed double sheet N°16, and latticework-type panels on the SUM and the galleries	
Fittings	Classrooms: 5 fluorescent 2 x 36 W tubes and 2 industrial wall fans. SUM: 9 industrial 250 W hanging lamps and 5 30" industrial wall fans	

Table 1. Constructive characteristics of the JI N° 174. Source: Preparation by the authors.

Figure 4. Natural ventilation layout. Interior and exterior photos of the SUM. JI 174. Source: Preparation by the authors.

Although the building typology studied is compact, the semi-enclosed spaces (SUM and corridors) allow diffuse daylighting and permanent cross ventilation through the rooms' interior and exterior windows. This, in turn, leads to inconveniences, like the entry of dust, ventilation, and lighting during unfavorable weather, acoustic problems, and water leaks on rainy days (Figure 4).

RESULTS AND DISCUSSION

ENERGY AUDITS

The monitoring period covered eight days, from Nov. 12th, 2012 at 1 pm to Nov. 19th, 2012 at 1 pm. Two opposite-facing rooms with the same constructive characteristics were analyzed (Figure 5). Room 2 (H18) had two exposed northwest-facing facades and glazed areas, and Room 3 (H19), with one southeast-facing exposed facade and glazed areas. Room 2 was occupied in the morning (from 8 am to 12:45 pm), with 24 children aged 3 and 4, and Room 3, in the afternoon (from 1:30 pm to 5:45 pm), with 22 children aged 4 and 5. The SUM (H20) was also monitored. Classes were held normally during the working week, except on the 15th, 16th, and 19th, since there were no classes. Data provided by the Provincial Billing Company (SECHEEP, in Spanish) indicated that the Kindergarten had a consumption of 909 kWh in November, this being the highest of the spring period.

Figures 6, 7, and 8 compare the internal and external variables measured concerning the regional comfort ranges.

The temperature curve trend of room 2 morphologically responds to changes in outside temperature, with very pronounced peaks and troughs, and is outside the

Figure 5. Left: JI 174 monitoring scheme. Period Nov. 12th, 2012 – Nov. 19th, 2012 Right.: Interior Room 2 (Violet), with NW-facing windows, and Room 3 (Light Blue), with SE-facing windows.

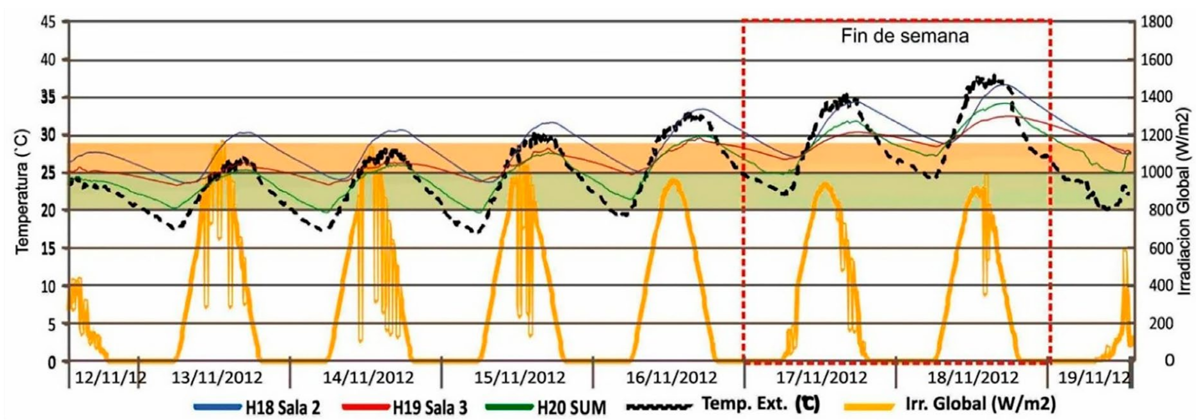


Figure 6. Evolution of internal temperatures. Classrooms JI 174. Period Nov. 12th. 2012 – Nov. 19th, 2012. Source: Authors' record.

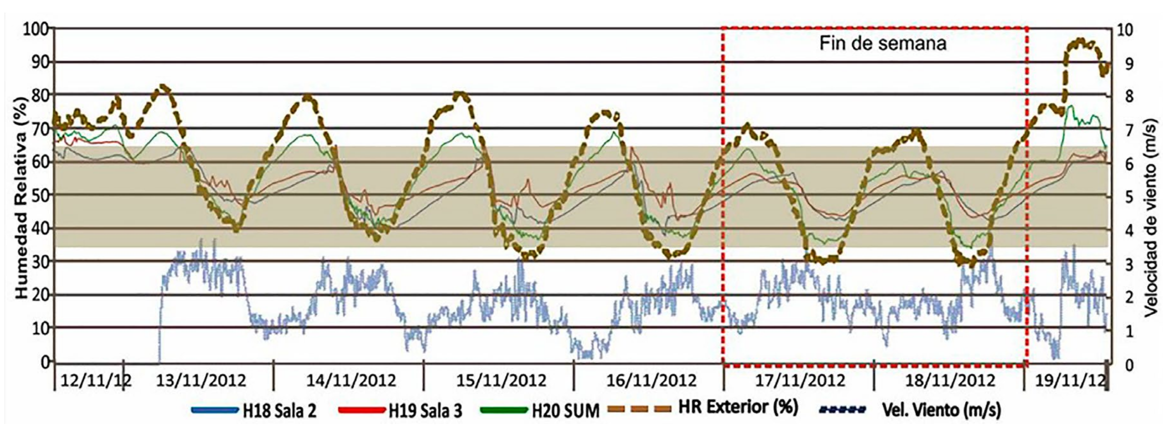


Figure 7. Relative humidity evolution. Classrooms JI 174. Period Nov. 12th, 2012 – Nov. 19th, 2012.
Source: Authors' record.

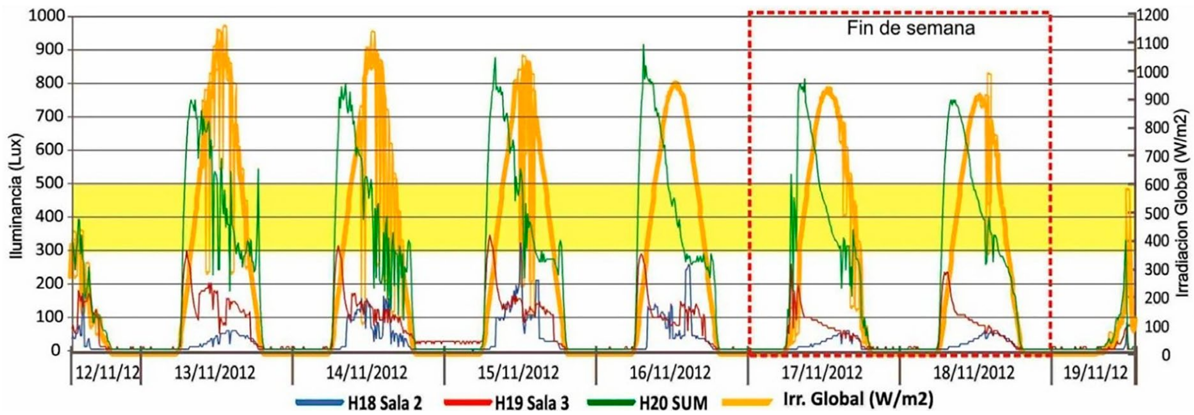


Figure 8. Evolution of illuminances. Classrooms JI 174. Period Nov. 12th, 2012 – Nov. 19th, 2012. Source: Authors' record.

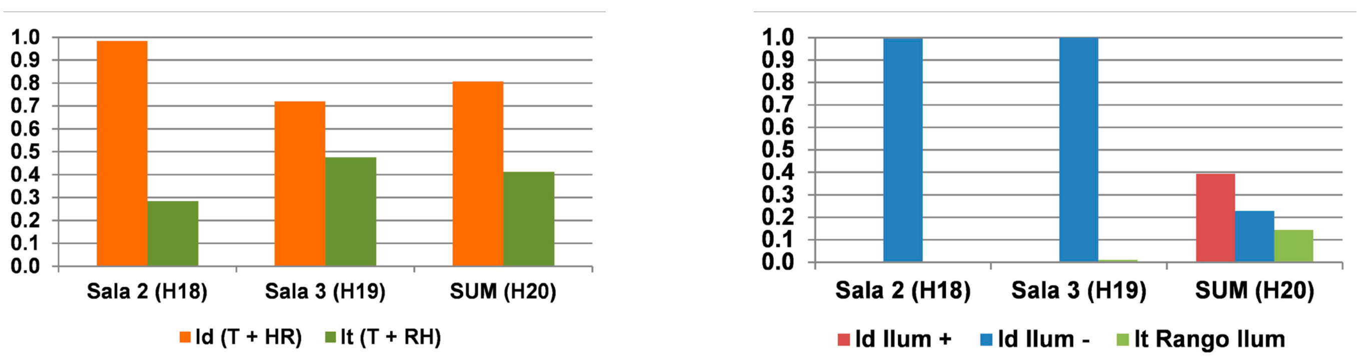


Figure 9. Comparison of combined hygrothermal indices (left) and light indices (right) of monitored premises JI 174. Period Nov. 12th, 2012 – Nov 11th, 2012. Source: Preparation by the authors.

upper comfort limit most of the time. Even though the occupancy schedule is from 8 am to 12:45 pm, this discomfort is confirmed from noon and remains until late at night in the first days, and during the 24 hours, in the last three days of monitoring. Its average values were 29°C – 50% RH, 7.4°C of thermal amplitude and 3.3°C of indoor-outdoor difference, and an average maximum of 32.7°C. The maximum internal temperatures occurred between 4 and 6 pm, while the maximum illuminances, between 2 and 3 pm, so the overheating produced is not due to direct solar gains. It is inferred that this is produced by the combined effect of the incident solar radiation on the entire opaque and glazed envelope and the outside temperature. The curve of room 3 has a more constant behavior since it receives sunlight in the morning, but it is occupied in the afternoon, observing small increases in the occupation hours (1:30 5:45 pm) that last until the evening. The SUM fluctuates almost accompanying the outside temperature, within the comfort band, except on warmer days. The relative humidity of the rooms is kept within the comfort zone, but the SUM exceeds the upper limit.

Consequently, in the period evaluated, room 2 with the largest exposed envelope area had the highest hygrothermal discomfort index [Id (T+RH)], a result of overheating, since it has glazed areas to the northwest, and its northeast facade is totally exposed to solar radiation. On the other hand, both rooms had the highest indices of visual discomfort due to a lack of daylight use [Id Ilum -] (Figure 9). The Id (T+RH) combined discomfort index by temperature and RH, is a relative index between the indoor and outdoor discomfort situation, calculated as the quotient between two observable frequencies. Its complement is the It (T+RH), temporary comfort index. The Light indices I_d *Ilum*$^-$, low illuminance discomfort index, I_d *Ilum*$^+$, excess illuminance discomfort index, and temporary visual comfort index $It_{(Ilum\ Range)}$, were calculated considering the established visual comfort ranges when the solar irradiation was greater than 500 W/m^2 (average value of sunny days). Its theoretical development can be consulted in the work of Boutet, Hernández, and Jacobo (2020).

RESULTS OF MODEL VALIDATION

In both simulation programs (Simedif V 2.0 and Radiance – Ecotect) the meteorological data measured in the considered period were entered and

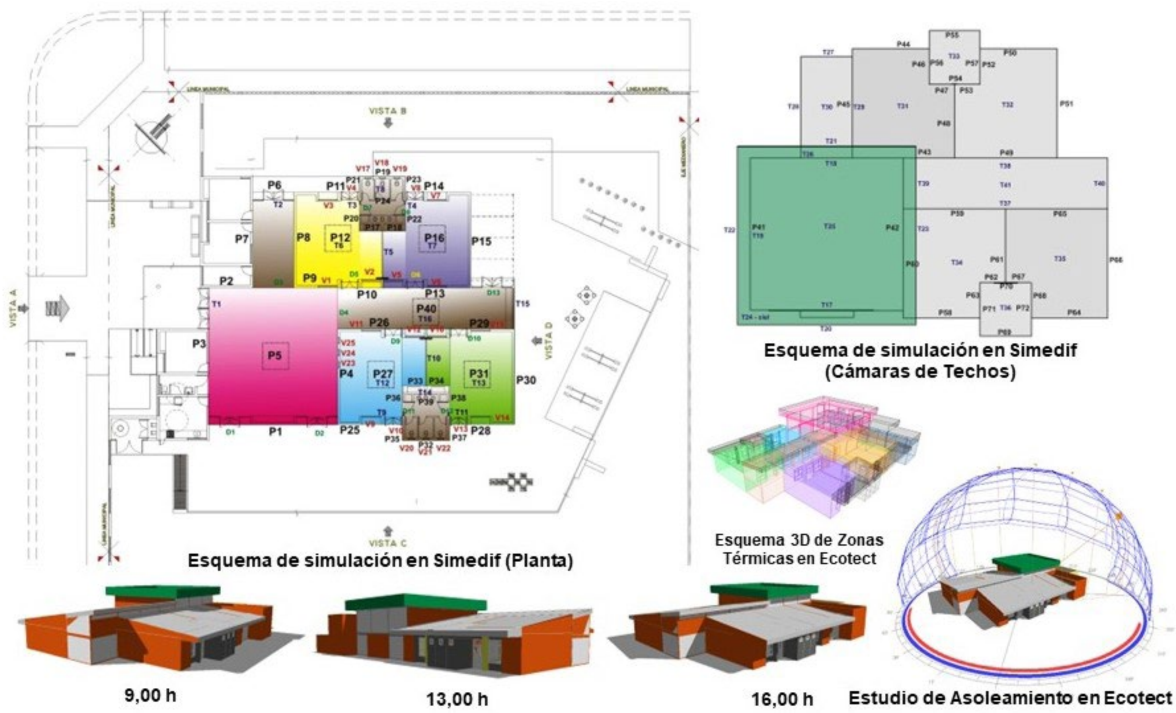


Figure 10. Simulation Models in Simedif and Ecotect. JI 174. Source: Preparation by the authors.

17 thermal zones were defined (Figure 10), including roof air chambers, with standardized parameters in terms of characteristics and physical properties of the building's opaque and glazed components.

Thermal Model. In the model set up in Simedif, 15 days of previous calculation were determined to reach the stable state and the following parameters were specified:

Gains/losses: This comes from people with a moderate level of activity and air conditioning devices, which deliver/extract heat, establishing their power, quantity, and period of use or occupation.

Air renewals (hourly; unit: 1/h): They were differentiated for each day and each zone, considering the voluntary air intake through windows, whose registration was between 0.5 and 4 during the night (without occupation) and between 4 and 10 during the day (with occupation).

Materials and properties of elements with mass and lightweight partitions: They were established from the list of materials available in the program (based on the Argentine IRAM Standards). For others that were not available, the physical properties obtained from tables (Incropera & de Witt, 1999), contrasted with the IRAM Technical Standards, were used.

Global convective/radiative heat transfer coefficients h (W/m2 °C): The external convection-radiation transfer coefficients were defined considering the average wind speed and regarding its impact on the building under study. These varied between 8 and 12 W/m^2°C. The internal values were obtained from Duffie and Beckman (1991), establishing 6 W/m^2°C for shaded surfaces; 8 W/m^2°C, for sunny surfaces; and 3 W/m^2°C, for the lower surface of the ceilings (layered air). For the windows, thermal transmittance of 5.8 W/m^2°C was applied, in the analyses without sun protection, and 2.8 W/m^2°C, in the analyses with protection (internal curtains).

Solar absorbance (value between 0 and 1): This was chosen based on the tables of Incropera and Witt (1999) and the color window provided by the software, determining a value of 0.65 for exposed brick walls, and 0.3 for light-colored surfaces.

Sunny areas: The use of the BIM model configured in Ecotect (Figure 10) contributed to its definition, which allowed obtaining the percentages of shaded and solar radiation-exposed surfaces. The irradiated internal areas were established as equivalent to the glazed area of the analyzed premises that the solar radiation passes through.

Lighting model. For the analysis of daylighting using the Ecotect Radiance interface, the most representative type of sky was defined considering the onsite measurement time, using the CIE (International Commission on Illumination) model. The calculation of the daylighting levels (lx) was made three times,

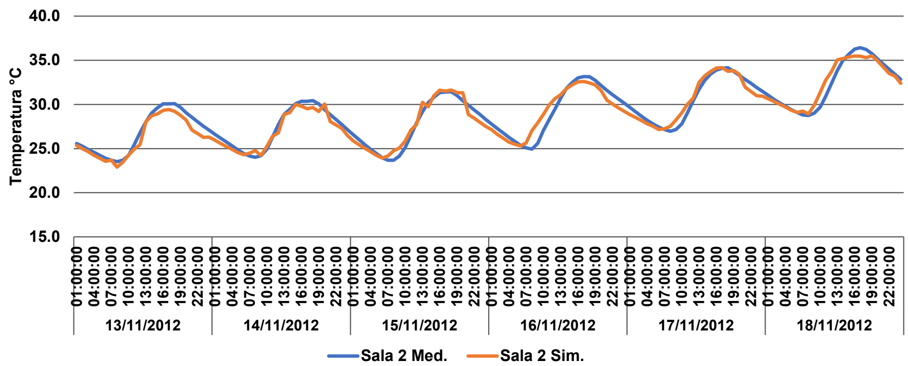


Figure 11. Contrast of measured and simulated temperatures. Room 2 JI 174, period Nov. 13th, 2012 – Nov. 18th, 2012. Source: Preparation by the authors.

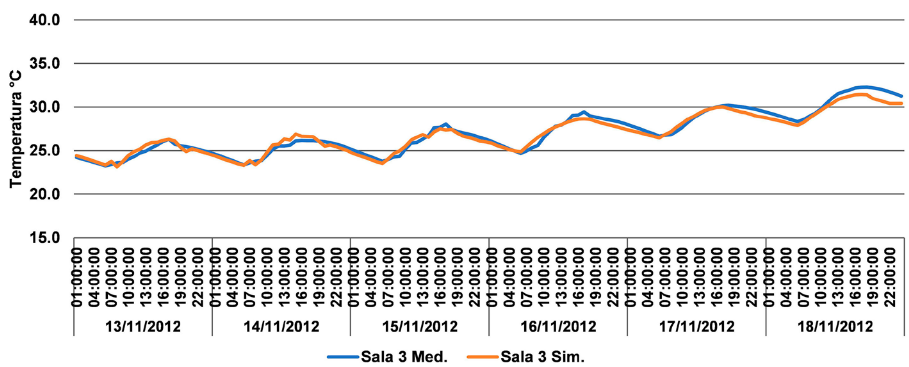


Figure 12. Contrast of measured and simulated temperatures. Room 3 JI 174, period Nov. 13th, 2012 – Nov. 18th, 2012. Source: Preparation by the authors.

JI 174 - NOV.	RMSE (T °c)			MAPE (T %)		
LOCAL	Full Per.	Class days	Days unoccup.	Full Per.	Class days	Days unoccup.
Room 2 (H18)	0.7	0.7	0.8	2.1	2	2.1
Room 3 (H19)	0.5	0.4	0.5	1.5	1.2	1.6
SUM (H20)	0.7	0.5	0.8	2.2	1.8	2.4
AVG. TOTALS	0.6	0.5	0.7	1.9	1.7	2.0

Day Nov. 14th, 2012			Meas. Illum (Lx)	Sim. Illum (Lx)	RMSE (LX)	MAPE (%)
Room 2 (H18)	1	9 am	114	111	17	30
	2	1 pm	83	79		
	3	4 pm	35	65		
Room 3 (H19)	1	9 am	99	108	8	6
	2	1 pm	130	141		
	3	4 pm	99	108		
SUM (H20)	1	9 am	777	931	114	18
	2	1 pm	430	552		
	3	4 pm	201	211		
TOTAL AVERAGES					46	18

Table 2. Adjustment between measured values and simulated values with SIMEDIF. Source: Preparation by the authors.
Table 3. Adjustment of illuminances day 14/11/2012. Source: Preparation by the authors.

at 9 am, 1 pm, and 4 pm on the sunniest day (Nov. 14th, 2012), in an analysis grid that was configured for each classroom at the height of the work plane (0.60 m for the children). Visualizations were established that represented the amount of incident light on each interior surface, with the illuminance values in "contour lines" and in "false color". To configure the use of internal curtains, the visible transmittance of the glazed areas was regulated following the different situations observed during the monitoring. Although this is a simplification, it was relevant for the required conceptual analysis, although a more detailed analysis is expected in future studies, for which the application of annual dynamic metrics is recommended, which would allow a better characterization of the visual environment.

As global averages of the evaluated premises, the values of the Root Mean Square Error - RMSE (°C) of the temperature of the premises simulated with Simedif show mean deviations of 0.6 throughout November, 0.5°C on the class days, and 0.7°C on the days without occupation. The total averages of the Mean Absolute Percentage Error - MAPE (%) are 1.9% in the full period, 1.7%, on class days, and 2.0%, on the days without occupation. In both cases, a greater adjustment was confirmed during school days (Figures 11 and 12; Table 2).

The differences in the illuminance averages measured and simulated using the Ecotect Radiance interface on the considered day resulted in an RMSE value of 46 Lx and a MAPE value of 18% on average (Table 3).

The global thermal and light adjustment orders found, demonstrate the validity of the physical models made in Simedif, using the Ecotect program as support for solar and lighting analysis, which allowed continuing with the testing of the generic proposal optimized for the case study.

OPTIMIZED GENERIC PROPOSAL

In the work of Boutet and Hernández (2021), after testing multiple improvement proposals for the audited cases, which were verified for the different seasons of the year, a Generic Proposal was defined with five alternatives and in two series (light and dark fittings), among which the so-called "*pg4*" was selected as the most optimal from the technical-economic point of view and its thermo-luminous behavior, to be applied to the case studies. The new values of *gA*, and *envelopeA* obtained in this research were used as input data for the Glazing Factor (*gF*) estimation tool, using Multivariate Linear Regression (MLR). In this second part of the research, the study of the proposal applied to Kindergarten No. 174 was developed further to verify its relevance, detecting the potential bioclimatic resources of the building and specifying the following design guidelines:

- Modification of the proportions of glazed areas in windows and doors for two weighted average solar absorbance values: *pg4* (= 0.65) with a glazed area of 5.05 m^2 and *pg4* (= 0.25) with a glazed area of 7.43 m^2, extracted from the input data corresponding to the *gF* estimation methodology (Boutet & Hernández, 2020). In this way, the GA/FA (Glazed Area / Floor area) improved from 7.4% when it did not meet the 10% value recommended by the Construction Regulations, to 11.3% in *pg4* (= 0.65) and 16.7% in *pg4* (= 0.25) and, consequently, the GA/FA (Glazed Area / Facade Area) values increased from the original 20% to 31% and 46%, respectively.

- Integrated design of solar protection devices in different geometric configurations appropriate for mid-orientation. Given that the building geometry of JI N° 174, with panels sunk and jutting out, generates a certain degree of solar protection to the openings, the (0.50 m wide) exterior light shelves solution was feasible with a reflective finish along the higher glazed panes (at 2.10 m in height), and an interior light shelf (0.40 m wide) to improve the daylight distribution and decrease the direct incidence, without losing the view of the outside. Only in cases of direct solar incidence, double roller shades are proposed, with the possibility of dimming light using a semi-see-through fabric. In Room 2, a pergola was incorporated into an existing structure attached to the Northeast facade.

- Increased airtightness of the SUM spaces and corridors through a translucent enclosure with Profilit – U double glazed self-supporting profile system, complemented with upper ventilation grilles, thus closing the opening system with fixed horizontal sunshades that were originally permeable to weather agents. In addition, upper projection windows with 3+3 laminated glass were incorporated along the northwest corridor, increasing the diffused light towards the rooms, and DVH windows with thermal bridge breakers in the openings to the outside.

- Regulation of air renewals (reduction or increase), according to the requirements of each classroom, considering that the type of ventilation proposed has a higher degree of airtightness and allows better management of natural ventilation.

Table 4 shows the dimensional variables of the original model of Room 2, with northwest-facing glazed areas, and the improvement proposals developed for the two solar absorbance values.

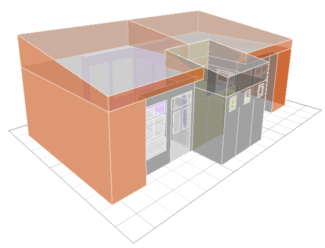
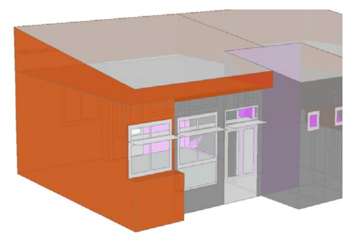
Room 2 – JI 174	ORIGINAL	Pg4 abs 0.65	Pg4 abs. 0.25
DIMENSIONS: Width: 7.20 m Length: 7.20 m Height: 3.00 m			
NORTHWEST FAÇADE OPENINGS SYSTEM	Top and central pane window with 2 sliding sheets and/or a fixed lower pane. Door with a fixed upper glazed pain and 2 folding glazed sheets	Top and central pane window with 2 sliding sheets and/or a fixed lower pane Sunken window with a 2 sliding sheet central and upper pane and/ or Door with a fixed upper pane and 2 folding sheets with fixed glass that total 1.53m2	2 sliding sheet windows and a fixed lower pane Sunken window with 2 sliding sheets Upper window pane with running projection. Door with 2 folding sheets with fixed glazing that total 1.80 m2
PROTECTION DEVICES	Eaves and flashes	External light shelves along the upper openings of 0.50 m width and interior of 0.40 m wide, eave projections, and side pergola	External light shelves along the upper openings of 0.50 m width and interior of 0.40 m wide, eave projections, and side pergola
OPENING PROPORTION (m)	Window: Width: 1.60; Height: 1.90 Door: Width: 1.4; Height 2.5	Window: Width: 1.60; Height: 1.90 Sunken window: Width: 1.60; Height 1.30 Door: Width: 1.4; Height 2.5	Window: Width: 1.60; Height: 1.90 Sunken window: Width: 1.60; Height 1.60 Sliding window: Width 5.10; Height: 0.45 Door: Width: 1.4; Height 2.0
GLAZING EF. AREA Without frames (m2)	3.29	5.05	7.43
WEIGHTED AVERAGE SOLAR ABSORBANCE (α)	0.57	0.65	0.25
TOTAL ENVELOPE AREA (envelopeA)	124.81	124.81	124.81
FLOOR AREA (m2)	44.52	44.52	44.52
FAÇADE AREA (m2)	16.2	16.2	16.2
GA/FA(%)	7.4	11.3	16.7
GA/FacA (%)	20.3	31.2	45.9

Table 4. Dimensional variables of the original model and the improvement proposals with different solar absorbance values. Source: Preparation by the authors.

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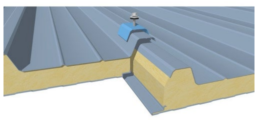
ILLUSTRATIVE DETAILS	GENERIC PROPOSAL (pg4)	Esp. (m)	Global Loss Coeff U (W/m2°C)	U (W/m2°C) IRAM Medium Level
	CEILING Self-supporting sheet metal plate with internal insulation thermal transmittance Coefficient (k) = 0.44 W/ m2°C * Reflective exterior finish.	0.081	0.4	0.45 (IRAM 11605: 1996)
	DOUBLE WALL: a sheet of ordinary brick, 0.12 m thick; insulation of 0.03 m thick expanded polystyrene (15 kg/m3); 0.12 m thick brick sheet finished with thick and thin plaster inside.	0.30	0.8	1.1 (IRAM 11605: 1996)
	DVH WINDOWS, laminated (6+12+6); aluminum profiles with RPT (U = 2.85 W/m2°C). Shading coefficient = 0.72; Visible transmittance = 0.81; Refractive index 1.526. * Devices for controlling and distributing daylight (eaves - light shelves)	0.024	2.8	from 2.01 to 3.00 (Medium-Level K4 IRAM 11507 4:2010)
	TRANSLUCENT Profilit / U-Glass double ENCLOSURES of 0.40 x 2.60 m and 4 mm thick; aluminum profiles with RPT. Shadow coefficient = 0.72; Visible transmittance = 0.81; refractive index 1.526.	0.082	2.8 (day and night)	

Table 5. Properties of the Generic Proposal of the JI 174 entered into Simedif. Source: Preparation by the authors.

- **Treatment of the opaque and glazed envelope using medium thermal inertia solutions** of known use in the NEA, following global loss coefficient (U) values recommended by the IRAM 11605: 1996 Standards for summer (most unfavorable situation) at the Middle level (B), and the design recommendations for Zone Ib, IRAM 11603: 2012. In this way, U = 0.8 W/m^2 °C was calculated for walls; U = 0.4 W/m^2 °C for ceilings; and U = 2.8 W/m^2 °C for windows, without the average level K4 (from 2.01 to 3.00 W/m2°C) (IRAM 11507 4: 2010). Table 5 details the generic proposal of the building with its characteristics entered into Simedif.

RESULTS OF THERMO-ENERGETIC SIMULATIONS

For each classroom analyzed, the temperature evolution of the respective proposals simulated using Simedif, obtained in November was plotted, comparing it with those measured from the original building (Figures 14 and 15). The green dotted line indicates the comfort limits established for the statistical analysis (20 - 27 °C) and the yellow dotted line indicates the maximum regional comfort limit (29 °C).

It is observed that the temperatures of the proposals remain most of the time within the comfort zone, with Room 3 (southeast) being in better conditions. Room 2 (northwest), leaves the regional comfort zone between 1 pm and 7 pm, but the temperature decreases considerably with respect to the original situation since, because as the northeast façade is fully exposed to solar radiation, it presented greater gains.

Comparing the original situation with the results of the *pg4* improvement proposal (= 0.25) considered optimal, the following thermal improvements were

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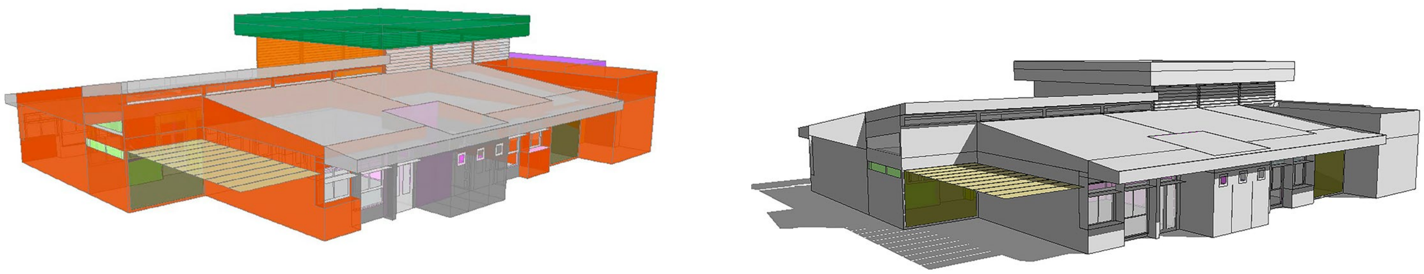


Figure. 13. Left. Model pg4 (= 0.65) – Right. Model pg4 (= 0.25). Source: Preparation by the authors.

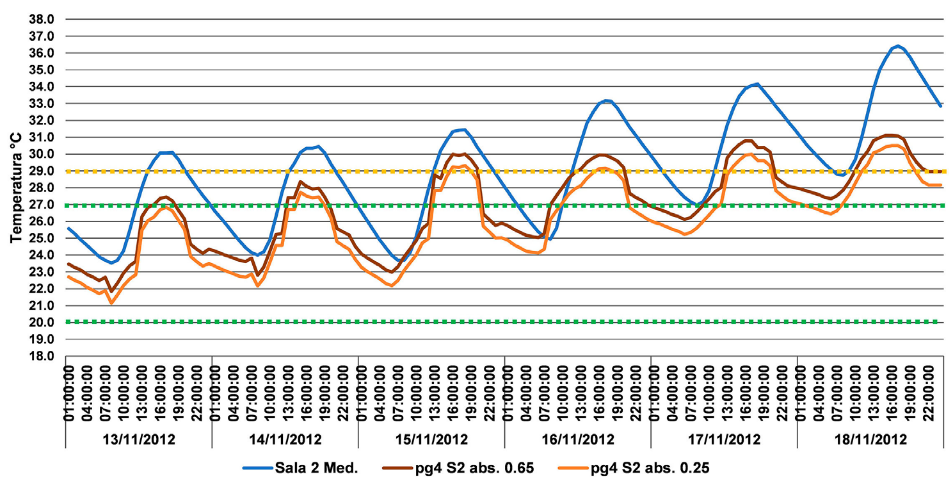


Figure 14. Evolution of simulated temperatures with the generic proposals (pg4), in contrast to the measured temperature (Room 2). Source: Preparation by the authors.

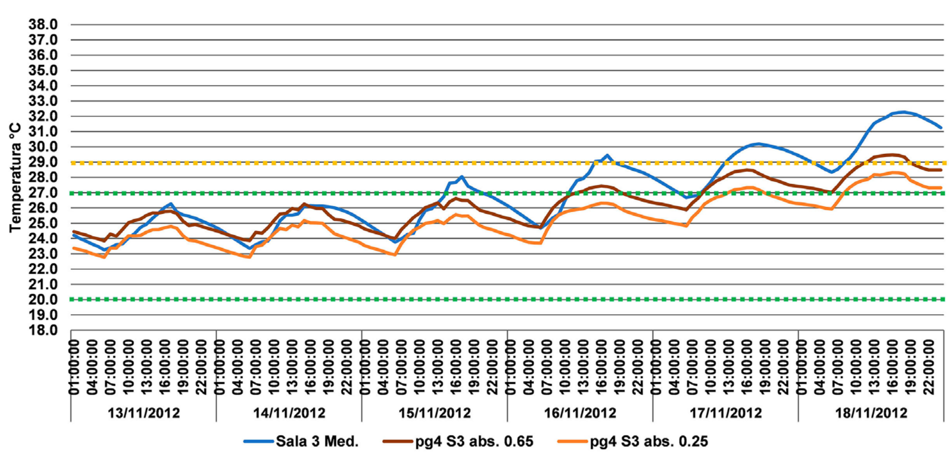


Figure 15. Evolution of simulated temperatures with the generic proposals (pg4) in contrast to the measured temperature (Room 3). Source: Preparation by the authors.

obtained in the analyzed November period: starting from a measured absolute maximum temperature of 36.4 °C and an average temperature of 29.0°C in Room 2, a reduction of 5.9°C and 3.0°C, respectively, was achieved. Based on a measured absolute maximum temperature of 32.3°C and an average temperature of 27.0°C in Room 3, a reduction of 4.0°C and 1.8°C, respectively, was achieved (Table 6).

These improvements in indoor temperatures were reflected in a drastic decrease in cooling loads in both proposals, verified by simulations with thermostatization (25°C) in Simedif, as well as the hours of discomfort where conditioning is required. Table 7 compares the maximum cooling requirements of both proposals with respect to the original simulated model, seeing a reduction of 72% for Room 2 and 51% for Room 3 with the proposed *pg4*

		Temp. Measurement (°C)	pg4 S2 - 0.65 (°C)	pg4 S2 - 0.25 (°C)	Dif. pg4 S2 - 0.65 (°C)	Dif. pg4 - 0.25 (°C)
ROOM 2	MAXIMUM	36.4	31.1	30.5	5.3	5.9
	AVERAGE	29.0	26.9	26.1	2.2	3.0
ROOM 3	MAXIMUM	32.3	29.5	28.3	2.8	4.0
	AVERAGE	27.0	26.2	25.2	0.7	1.8

Table 6. Comparison of measured maximum and average temperatures and simulated proposals. Source: Preparation by the authors.

LOCAL	gA Orient	Original (W)	pg4 0.65 (W)	pg4 0.25 (W)	Difference (Original - pg4 0.65)	Difference (Original - pg4 0.25)	% Reduction pg4 0.65	% Reduction pg4 0.25
ROOM 2	NO	10600	3084	2985	7516	7614	71	72
ROOM 3	SE	2740	1455	1331	1285	1410	47	51

Table 7. Reduction of cooling loads, November period. Source: Preparation by the authors.

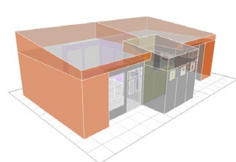
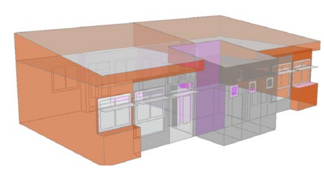
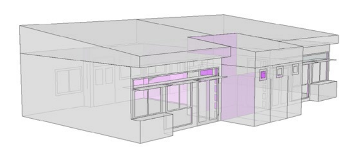
JI 174 NOVIEMBRE						
	MEDIDA		pg4 abs. 0.65		pg4 abs. 0.25	
AVERAGES	Ilum. (Lux)	Temp. (°C)	Ilum. (Lux)	Temp. (°C)	Ilum. (Lux)	Temp. (°C)
Room 2	77	27,8	487	26,3	599	25,6
Room 3	109	25,2	557	25,6	572	24,6
RANGOS	Ilum. (Lux)	Temp. (°C)	Ilum. (Lux)	Temp. (°C)	Ilum. (Lux)	Temp. (°C)
Room 2, 9:00 h.	114	24,2	476	23,3	563	22,6
Room 2, 13:00h.	201	28,9	551	27,4	648	26,7
Room 2, 16:00h.	319	30,3	433	28,1	585	27,5
Room 3, 9:00 h.	99	23,8	610	24,7	564	23,9
Room 3, 13:00h.	130	25,5	596	26,0	630	24,9
Room 3, 16:00h.	99	26,2	466	26,1	523	25,0

Table 8. Comparative results of thermal-light simulations (11/14/2012) on average and by hourly ranges.
Source: Preparation by the authors.

(= 0.25). The remarkable improvement obtained in Room 2 is verified by reducing the exposed area of the opaque envelope and the solar absorption of the exterior surfaces.

THERMAL-LIGHT COMPATIBILITY OF RESULTS

When analyzing the thermal-light compatibility in the three evaluated schedules (9 am, 1 pm, and 4 pm) on the sunniest day, Nov. 14th, 2012 (Table 8), it is noted that through the improvement proposals, the increase in the illuminance averages was verified with respect to the original model that did not reach the minimum values. The *pg4* (= 0.65) enters the thermal-luminous comfort zone (between 20°C and 27°C and from 300 to 500 lux), while the *pg4* (= 0.25) slightly exceeds the visual comfort limit given the higher GA/FA percentage, although without leaving the thermal comfort zone. Even though this would not generate glare problems, since a maximum illuminance of 750 lx is accepted, the values could be corrected through the use of translucent internal curtains

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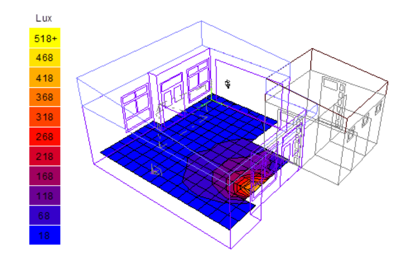
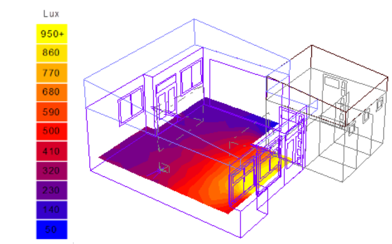
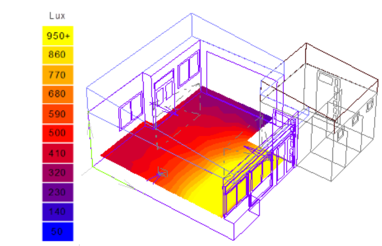
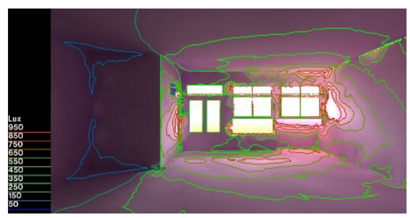
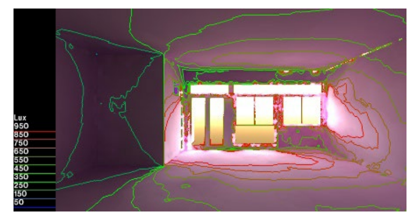
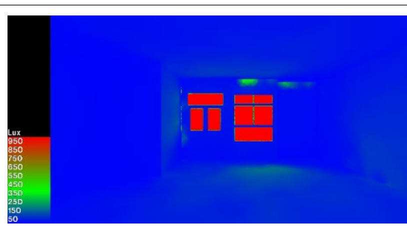
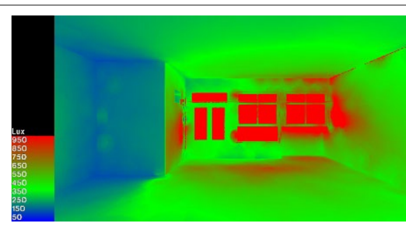
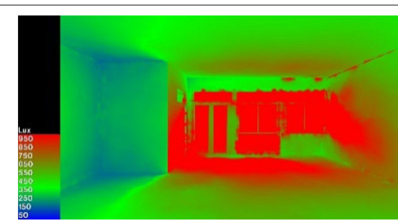
ORIGINAL MODEL	IMPROVED pg4 abs. 0.65	IMPROVED pg4 abs. 0.25
		
		
		
Ilum. = 114 lx	Ilum. = 476 lx	Ilum. = 585 lx

Table 9. Comparative results of thermal-light simulations on average - Room 2 (Day 14/11/2012 – 4 pm). Source: Preparation by the authors.

at times of greater solar incidence. As an example, Table 9 shows the visualizations obtained for the original Room 2 model and the improved ones, on the sunniest day, Nov. 14th, 2012 at 4 pm, when the sun hits the northwest facade.

CONCLUSIONS

The verification made using dynamic simulation models, calibrated with onsite measurements, allowed demonstrating the relevance of the glazed areas proposed for different solar absorbance values of the outside exposed surfaces of the case study, and to preliminarily validate the estimation methodology of the Glazing Factor (*Fv*) for the Compact Kindergarten Typology. This connected the most important variables in play (*Av*, α and *envelopeA*) and makes it possible to determine glazed areas that would lead to optimal thermal and light behavior.

In particular, a reduction of cooling requirements of up to 72%, in November, the most unfavorable for a school activity, was obtained by lowering the solar absorbance of outdoor surfaces to 0.25 (light colors), with a glazed area by the floor area ratio of 17 % (northwest and southeast), that allowed significant improvements in the spatial distribution of daylight, a key resource for the integrated development of children in Initial Schooling Level.

This finding extends that established by the current Resistencia Construction Regulations, which determines only a minimum *gA* of 10% of the floor area, without considering the intermediate orientation of the city, or the other project variables (total envelope area and exterior solar absorption). In this way, the *gF* estimation tool can become a valuable resource for professionals in the education sector, as well as for updating municipal or provincial regulations in the NEA Region.

However, the iteration process to calculate other typologies different from the reference one could be laborious since the *gF* correlations were obtained with limited input data, so it will be necessary to continue testing other initial-school-level typologies and in other possible orientations, to expand the database and improve the operation of the corresponding correlation, insofar as it constitutes a feasible modification methodology with new inputs.

Considering the compatibility of the proposed thermal and light improvements, the importance of the optimized solar protection design of window devices, and integrated environmental regulation systems are highlighted, which together with the treatment of the opaque envelope, and the morphological layout of the building, allow its adaptation to a wide range of climatic conditions and responsible for the use of such as powerful renewable energy source in the NEA Region, as solar is.

The degree of fit obtained regarding the data taken onsite, from the dynamic simulation models made using the Simedif software, in real occupation conditions, with mean deviations of 0.6°C (RMSE) and errors (MAPE) that do not exceed 2%, contributed to the accuracy of the results. Likewise, the Ecotect Radiance interface was a contribution, with average errors of 46 Lx (RMSE) and 18% (MAPE), admissible in terms of illuminances. This makes it feasible to test other periods not yet measured reliably, based on weather data collected in the urban microclimate of Resistencia.

Facing the future global warming scenarios, and the evident need for updating comfort standards at a local and Latin American level, but also taking into account the particularities of different educational levels, in this case, the Initial Schooling Level, the results of this research represent a scientific level record, available for its main beneficiary, the Ministry of Education, Culture, Science and Technology of the Province of Chaco, which may well be extended to other regions with a Very Warm – Humid subtropical climate, in pursuit of the sustainable design school spaces.

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QUALITATIVE ANALYSIS OF THE SOCIAL SUSTAINABILITY OF URBAN DRAINAGE SYSTEMS IN CHILE

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ANÁLISIS CUALITATIVO DE SOSTENIBILIDAD SOCIAL DE SISTEMAS DE DRENAJE URBANO EN CHILE

Gianina Hidalgo-Monroy
Estudiante de Ingeniería Civil, Departamento de Obras Civiles, Universidad Técnica Federico Santa María
Santiago, Chile
https://orcid.org/0000-0001-9776-3191
gianina.hidalgo.14@sansano.usm.cl

Sebastian Vasquez-Avila
Estudiante de Magíster en Ciencias de la Ingeniería Civil, Departamento de Obras Civiles, Universidad Técnica Federico Santa María. Valparaíso, Chile
https://orcid.org/0000-0002-5906-3490
sebastian.vasqueza@usm.cl

Felipe Araya
Doctor en Ingeniería Civil, Académico, Departamento de Obras Civiles, Universidad Técnica Federico Santa María
Valparaíso, Chile
https://orcid.org/0000-0001-9814-5184
felipe.araya@usm.cl

RESUMEN

Avanzar hacia un desarrollo urbano sostenible conduce a aplicar nuevas formas de drenaje, las que entregan múltiples beneficios técnicos y sociales a la comunidad. No obstante, en países como Chile aún existe una gran brecha respecto de metodologías de evaluación de sostenibilidad social de proyectos de drenaje urbano. A través del análisis cualitativo de contenido aplicado a entrevistas a expertos (*n = 11*), este estudio busca (1) identificar métricas para la medición de la sostenibilidad social de sistemas de drenaje urbano; (2) identificar desafíos para la implementación de dichas métricas y (3) proponer modificaciones al método actual de evaluación de sistemas de drenaje para mejorar la inclusión de la sostenibilidad social en el primero. Dentro de los resultados se advirtió que expertos proponen métricas que capturan la sostenibilidad social, pero que, en la práctica, son complicadas de cuantificar. En términos de los desafíos, la fragmentación de responsabilidades de las organizaciones que participan de la gestión de sistemas de drenaje dificulta el uso de nuevas métricas de sostenibilidad social. Por último, se sugiere el desarrollo de una institución que pueda gestionar los sistemas de drenaje urbano de forma global e integral a fin de valorar los beneficios de la sostenibilidad social de sistemas de drenaje urbano. Estos resultados pueden ser utilizados por autoridades y tomadores de decisiones relacionados a sistemas de drenaje urbano para desarrollar nuevas metodologías que tomen en cuenta los beneficios de la sostenibilidad social.

Palabras clave
análisis cualitativo, desarrollo urbano, desarrollo sostenible.

ABSTRACT

Moving towards sustainable urban development leads to applying new forms of drainage, which provide multiple technical and social benefits to the community. However, in countries like Chile, there is still a large gap regarding methodologies to assess the social sustainability of projects in this area. Using a qualitative content analysis applied to experts' interviews (*n = 11*), this study aims at (1) identifying metrics to assess the social sustainability of urban drainage systems; (2) identifying challenges for the implementation of such metrics, and (3) proposing changes to the current system, to assess urban drainage systems that enhance the integration of social sustainability within these systems. The results show that experts proposed metrics that may assess social sustainability, but in practice, these metrics are difficult to quantify. In terms of challenges, the fragmentation of responsibilities from organizations that are involved in managing urban drainage systems may complicate the use of new social sustainability metrics. Ultimately, it is suggested that an institution is created that can manage urban drainage systems using an integrative approach, to account for the benefits of social sustainability of urban drainage systems. These results can be used by authorities and decision-makers who work with urban drainage systems, to move towards methodologies that consider the benefits of social sustainability.

Keywords
Qualitative Analysis, Urban Development, Sustainable Development, Chile.

INTRODUCTION

Urbanization is a historical natural development process and constitutes the largest human impact on natural watersheds since it leads to the loss of their natural ability of infiltration, subsurface storage, and evapotranspiration from the soil; processes that are replaced by an increased generation of direct surface runoff, which significantly affects the dynamics of the water cycle and water quality (Ministry of Public Works [MOP, in Spanish], 2013). In Chile, the urbanized area has increased by 39.5% between 2002 and 2017, a growth that is equivalent to the area of Greater Santiago (National Institute of Statistics [INE, in Spanish], 2019). It is also estimated that by 2050, the country's urban population will be 94.2% (MOP, 2013).

It is because of this that the need arises to generate a change in urban drainage management, integrating sustainability into urban planning as a tool to incorporate drainage systems that provide complementary benefits to traditional ones and, thus, to the communities they serve (Jato-Espino, Toro-Huertas & Güereca, 2022). The concept of sustainability aims at meeting the needs of current generations without jeopardizing the ability of future generations to respond to their needs (Brundtland, 1987; Olawumi & Chan, 2018). In this sense, sustainability has three dimensions that define it: the economic, the environmental, and the social (Sierra, Pellicer & Yepes, 2017; Valdes-Vasquez & Klotz, 2013). To achieve sustainable development, these three dimensions must be comprehensively addressed (Olawumi & Chan, 2018). However, in general, this does not happen, mainly due to the complexity of defining what social sustainability is, which hinders its measurement process (Atanda, 2019). Efforts are therefore required to develop a better understanding of how to capture and measure the concept of social sustainability. Given this context, this study seeks to analyze how social sustainability can be measured in the context of urban drainage systems in Chile. As a starting point, a review of the specialized literature on sustainable urban drainage systems is made, as well as on the concept of social sustainability, and the Chilean context of urban drains.

LITERATURE REVIEW

SUSTAINABLE URBAN DRAINAGE SYSTEMS

Replicating the different components of the existing natural water balance as much as possible, before urbanizing, generates urban drainage solutions that allow not only providing control of the quality and amount of runoff but also providing a more complete service to the community, aimed at improving the quality of life of city dwellers (MOP, 2013). This is the main objective of Sustainable Urban Drainage Systems (SUDS), which seek to manage urban runoff and, at the same time, provide improvements in green areas and environmental quality. According to the official guide in the UK (The SUD Manual), the 4 pillars of design in this framework are (1) Control of the amount of water, management of the flood risk, and maintenance and protection of the water cycle; (2) Management of the runoff quality; (3) Creation and maintenance of better spaces for the people; and (4) Creation and maintenance of better spaces for nature (Woods-Ballard *et al.*, 2007).

The mode in which sustainable drainage systems operate involves managing stormwater as close as possible to its source, reducing runoff, firstly, by infiltration and, when that is not possible, by retention, storing said waters temporarily and then discharging them in a controlled way (Woods-Ballard *et al.*, 2007). Its elements seek to represent the different components of the water cycle, based on the processes of infiltration, evapotranspiration, and water storage. Some examples of these are retention ponds, infiltration trenches, permeable pavements, and green roofs. These can be used individually or grouped into systems, whose configuration will define their effectiveness (Johnson & Geisendorf, 2019).

The technical benefits of these methods aim at reducing the presence of pollutants in surface water bodies, improving the quality of storm runoff, and promoting the recharge of aquifers, in addition to controlling floods (Gogate, Kalbar & Raval, 2017). Economic benefits are also produced by reducing both the costs of treating pollutants in water, as well as energy consumption (Jiang, J. Li, H. Li, Y. Li & Zhang, 2020).

Among the social and environmental benefits are the beautification of landscapes and the generation of habitats for native flora and fauna (Fajardo, Valdelamar & Mouthon, 2019; Jiang *et al.*, 2020). Surveys conducted in the United Kingdom (Jose, Wade & Jefferies, 2015) show that citizens value the biodiversity, health, and aesthetics provided by this infrastructure the most, since access to green areas provides pleasant recreational spaces, where you can walk or play, providing a sense of mental and physical well-being. Due to the aforementioned benefits, SUDS must have a place in city development, as they imply an important advance towards environmental and, above all, social well-being.

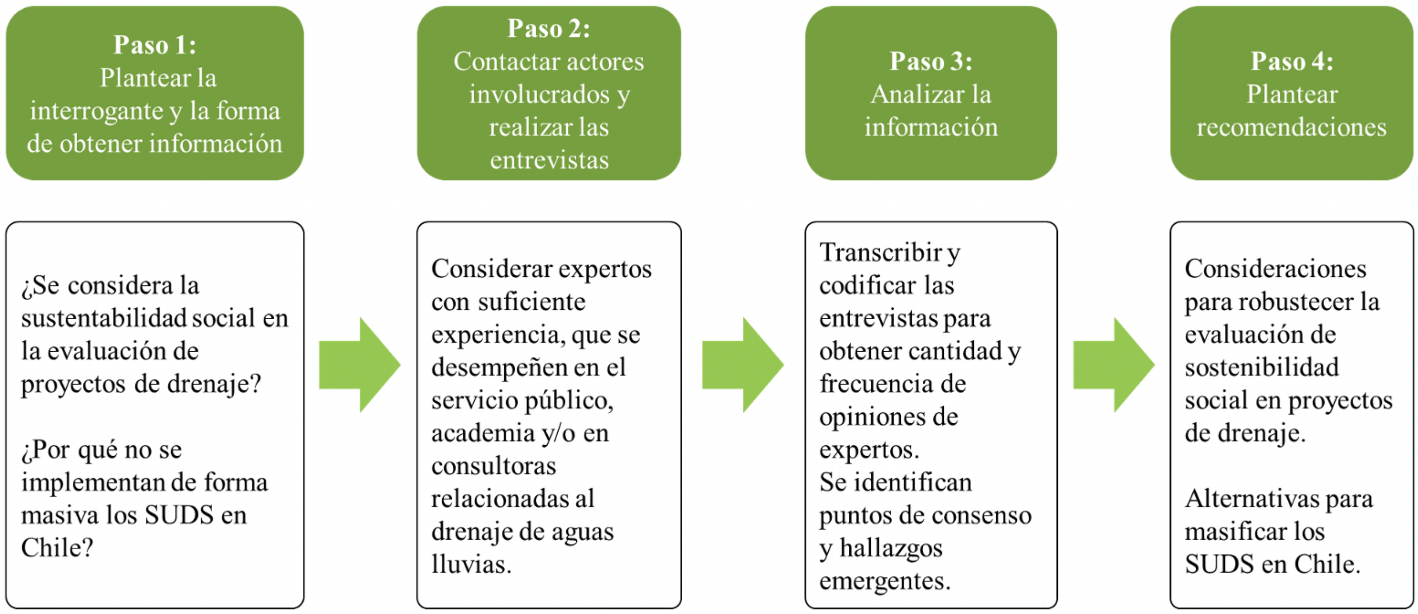

Figure 1. Summary of research steps followed in this study. Source: Preparation by the authors.

SOCIAL SUSTAINABILITY

Social sustainability is a concept that underlies multiple areas of knowledge and that assumes social development as the path to achieving greater equality, safety, and social responsibility, placing special emphasis on city development (Eizenberg and Jabareen, 2017). To achieve social sustainability, specific actions and policies must be contemplated that protect people, regardless of their origin, culture, or beliefs, to generate a greater community and a sense of belonging for the citizens (Vallance, Perkins & Dixon, 2011).

Social sustainability is evaluated through multicriteria evaluation methods since it seeks to represent the multidimensionality of reality through a diversity of perspectives, which determine its state of development (Jiménez *et al.*, 2019; Sierra, Yepes & Pellicer, 2018). Social criteria are the result of the grouping of indicators or principles that value a social aspect. However, their definition is not fully specified, since there are no pre-established social criteria that are valid for all contexts. The basic criteria of social sustainability are usually: equality, economy, local development, mobility and accessibility, health, poverty reduction, and environmental security. They have integrated new concepts, such as happiness, quality of life, the sense of belonging, and well-being (Chini, Canning, Schreiber, Peschel & Stillwell, 2017; Shen, Ochoa, Shah & Zhang, 2011) which, in turn, are more difficult to measure due to their intrinsic subjectivity (Atanda, 2019; Lami & Mecca, 2021). The assessment should analyze the entire life cycle of the structure, considering future needs; otherwise, the scope of social sustainability will be limited (Sierra *et al.*, 2018). However, some studies have focused on the social sustainability of specific stages of the life cycle of urban drainage systems, such as maintenance (Gogate *et al.*, 2019) and its more sustainable alternatives.

Another fundamental aspect for the development of metrics capable of measuring social sustainability is the participation of the different stakeholders (Axelsson *et al.*, 2013; Sierra *et al.*, 2018), people or organizations that may affect or be affected by the development of a project (Chinyio & Olomolaiye, 2009). The stakeholders to be considered in infrastructure projects may include local communities, NGOs, political representatives, infrastructure agencies, and experts in the infrastructure systems under study (Araya, Faust & Kaminsky, 2020; Chinyio & Olomolaiye, 2009; Valdes-Vasquez & Klotz, 2013). Therefore, it is key to understand how each of the stakeholders associated with infrastructure projects understands social sustainability. In the context of urban drainage systems, the specialized literature has rarely included the role of the different stakeholders. Indeed, in the bibliographic review evaluated by Ferrans, Torres, Temprano, and Sánchez, (2022), it was identified that the vast majority of studies in this area did not include the role of stakeholders (86% of the analyzed texts), and of the 14% that did, most considered the role of experts in urban drainage systems or authorities. Obviously, this emphasizes the role of experts in the development of a better understanding of the sustainable development of urban drainage systems.

Having suitable metrics is essential for a better evaluation of social sustainability, as it allows specifying and expanding the range of benefits, supporting them with objective data, and reducing the bias that user surveys could have (Jarvie, Arthur & Beevers, 2017). This is why

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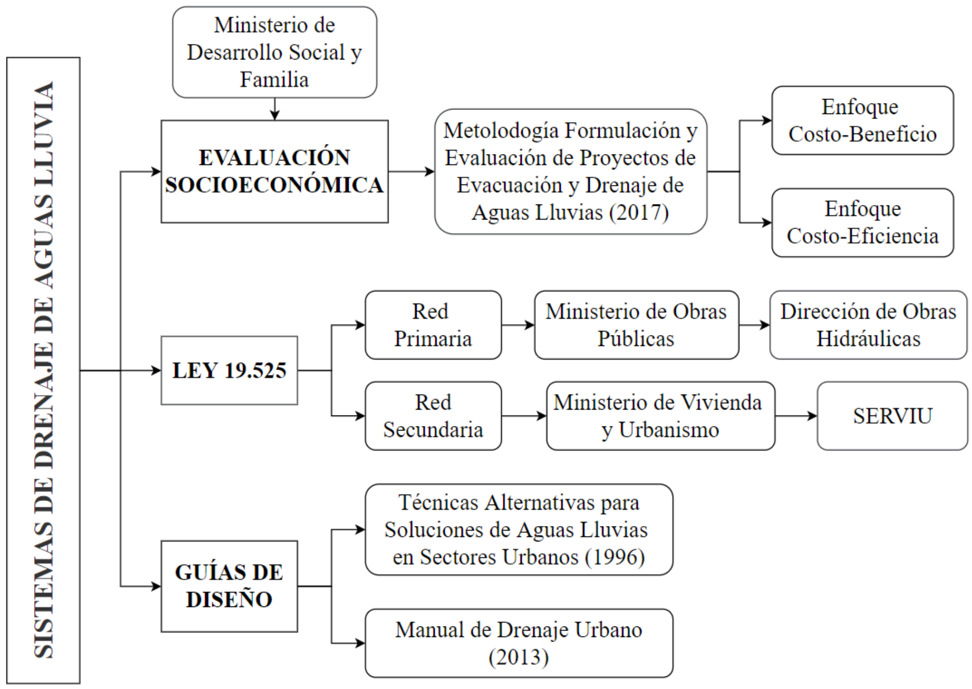

Figure 2. National context of urban drainage. Source: Preparation by the authors.

it is necessary to make studies in diverse contexts, such as the Chilean one, to contribute to the evaluation of social sustainability. Figure 1 shows a summary of the steps followed to make this study.

CHILEAN CONTEXT OF URBAN DRAINAGE

In 1997, the Chilean law regulating Rainwater Evacuation and Drainage Systems was passed. This emphasizes the reduction of flood damage in cities through the construction and operation of rainwater drainage infrastructure, which is independent of the wastewater network (Law No. 19.525, 1997).

It also divides the rainwater network into primary and secondary networks. The first is defined in the master plans and corresponds to natural channels and large diameter pipes, built and operated by the Public Works Ministry (MOP, in Spanish) through the Directorate of Hydraulic Works (DOH, in Spanish). On the other hand, the rest of the network is considered secondary, and its construction and operation depend on the Housing and Urbanization Service (SERVIU, in Spanish) (Law N° 19.525, 1997).

The Ministry of Social Development and Family (MIDESO, in Spanish) makes the technical-economic evaluation using the evaluation methodology of public urban drainage projects (MIDESO, 2017). The evaluation approach is the cost-benefit approach for investment projects greater than 30,000 UF[1;] otherwise, the cost-efficiency approach is the one used. The social benefits are evaluated, such as resource release and benefits for reduced flood damage, valued through the avoided damage and hedonic prices methodology. The relationship between the institutions responsible for urban drainage is illustrated in Figure 2.

The evaluated benefits make it difficult to finance projects that contemplate social benefits unrelated to the damages avoided by flooding, generally provided by sustainable drainage, such as aquifer recharge, water purification, and aesthetic and recreational aspects that contribute to the well-being of the population, which, on the other hand, are difficult to value.

For all the above, this study intends to address the limitations of the existing methodology for evaluating the social benefits of rainwater drainage projects, analyzing the current state-of-the-art, and exploring the level of awareness of experts and stakeholders. Based on the Chilean case study, it is expected to determine the main shortcomings of the current methodology, as well as the improvements that could be considered to strengthen it.

1 UF: Unidad de Fomento or Unit of Foment is an inflation-indexed unit of account, calculated and published by the Central Bank of Chile (BCCh)

	Field	Job title or position	Years of experience
1	Academia	Head of Academic Department	18
2	Academia	Professor	25
3	Academia	Researcher	1
4	Public institution	Social Assessment Analyst	16
5	Public institution	Head of Social Assessment Department	10
6	Public institution	National Infrastructure Manager	25
7	Public institution	National Infrastructure Manager	15
8	Public institution	Head of Technical Division	26
9	Public institution	Head of Technical Unit	15
10	Public institution	Head of Community Interaction Unit	17
11	Engineering/Consulting	Consulting engineer	1.5

Table 1. Characterization of the expert panel. Source: Preparation by the authors.

METHODOLOGY

DATA COLLECTION THROUGH INTERVIEWS

Given the importance of taking into account the different stakeholders in the development of sustainable urban drainage systems, in this study, it was decided to focus on one stakeholder in particular: experts in urban drainage infrastructure systems.

The experts were contacted via email and the interviews were mostly conducted remotely, lasting between 30 and 45 minutes. The interviews were recorded and then transcribed, with the interviewee's permission to do so. The selection criteria of interviewees were that in their work, they were linked either with urban drainage, social evaluation of projects, or sustainable urban infrastructure development, through academic, consulting, or institutional organizations. The last three are very important, as they provide knowledge from the operational perspective of the system. In this way, a total of 11 successfully completed interviews were obtained.

The sampling method of semi-structured interviews was chosen because it allows for a dynamic and flexible interaction between the interviewer and the interviewee.

The interviews sought to answer the following 3 questions:

1. What metrics could be used to assess sustainability, in general, and the social sustainability of sustainable urban drainage systems?
2. What barriers are there in the implementation of such metrics?
3. What modifications would you make to current measurement systems?

The expert panel was classified according to their field and years of experience, which on average was 15.4 years (Table 1).

QUALITATIVE ANALYSIS OF INTERVIEWS

The interviews were transcribed and analyzed qualitatively using the Weft QDA program. The answers were coded according to their most recurrent topics, using the live coding method (Saldaña, 2013). The coding was developed until reaching the saturation point, where new interviews only provided marginal information regarding the topic under study. This situation is in line with what the literature suggests, namely that this saturation point is reached at around 12 interviews (Galvin, 2015). To determine the frequency, explicit ideas were considered through content analysis (Namey, Guest, Thairu & Johnson, 2008). Finally, the codes were grouped according to the data-driven approach (Namey *et al.*, 2008), that is, around the relationship observed between them, evidenced in the answers of the interviewees. Each code used appears in Table 2 and considers five categories: environmental benefit, social benefit, social equality, difficulties, and aspects to be improved. It is important to underline that the five categories observed in Table 2 emerged from the analysis of the interviewees' responses. Similarly, it should be noted that, although one of the

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		Criterion	Definition	Response example
EVALUATION METRICS	ENVIRONMENTAL BENEFITS	Water quality	Quality of rainwater drained into water bodies.	"...water purification to avoid the contamination of water bodies due to the entry of pollution..."
		Amount of water	Rainwater that generates storm runoff.	"...contributing to holding back the accumulated water and not generating a greater peak …"
		Heat island effect	Temperature increase suffered by urban centers.	"...reducing the heat island effect, as it improves the ventilation of the city..."
		Aquifer recharge	Infiltrate water into the groundwater.	"...the infiltration of rainwater generates a benefit in the water resource; in a dry period, the value of stored water is quite important..."
		Reuse of water resources	Avoid using other water sources by using rainwater.	"...increasing the water retention of the soil, as it can be used to reduce the use of other water sources for irrigation..."
	SOCIAL BENEFITS	Amenity, aesthetics, and community benefits	Better integration of infrastructure in communities.	"...quality of life, aesthetic elements, recreational, and even spiritual ones, which mean living more harmoniously with the water in the city..."
		Public information, education, and awareness-raising	Educating the community about the role of urban drainage	"...now, it is seen that society is demanding this since they are more aware..."
	SOCIAL EQUALITY	Access to green areas	Standardizing access to green areas.	"...there is a large shortfall of green areas, not distributed homogeneously both at the country and the regional level and between regions..."
		Access to water	Standardizing the access to water.	"...if there is no water, there will be no food, it's that simple. There can be places that do not have access or that have a deficit regarding some of these issues..."
BARRIERS OR DIFFICULTIES FOR IMPLEMENTATION	Availability of resources	Availability of information	Databases for decision making.	"…availability and richness of data that is available to guide methodologies in that direction (sustainability).."
		Availability of resources	Resources to manage the infrastructure.	"...it is difficult due to the availability of information, calibration, and measurements. It is complicated to have the resources to obtain those data..."
		Fragmentation of responsibilities	Unclear division of responsibilities between agencies; these do not follow the same goal.	"...a recognition of the entire water cycle is required, that the drop that falls over there gets here..."
		Evaluation methodologies	Limited range of benefits assessed.	"...methodology for integrated projects and that capture other benefits that are just from rainwater and the flood damage avoided..."
		The rainwater paradigm	Way of conceiving solutions to rainwater drainage.	"...to change the paradigm of water that falls on the city, not to remove it quickly, but to integrate it into the urban water cycle..."
		Professional preparation	Insufficient training for professionals	"...there is a lack of interest or knowledge, there is always a bit of inertia, the same thing is done because everyone does the same thing..."

	Criterion	Definition	Response example
MODIFICATIONS OR ASPECTS TO BE IMPROVED	Global water entity	An integrated organization that plans infrastructure for rainwater.	"...rainwater does not have a primary or secondary network. It would be ideal to have an entity dedicated to comprehensive planning..."
	Secondary standards	Standards whose objective is to maintain and protect water quality.	"...the more secondary standards there are, the more we are going to worry not just about industries, but also about cities..."
	Planning on a household scale	Design of houses with sustainable drainage.	"...that runoff could be avoided if every time we urbanize, we take care to locally control the runoff that occurs..."
	Comprehensive valuation of benefits	Expand the range of benefits evaluated.	"...for the principles (of sustainability) applied to be transferred, it is important to have methodologies that consider them..."

Table 2. Code Dictionary. Source: Preparation by the authors.

categories included in Table 2 (i.e., environmental benefits) does not belong to the concept of social sustainability, it was incorporated anyway because it was integrated into the first question asked to the interviewees (see the previous section). It should be emphasized that even though this category is presented here (Table 2), as it emerged from the interviews, the focus of this study was always on social sustainability.

LIMITATIONS

Within the limitations of this study, it is contemplated, first of all, that the results may present a bias due to the number and origin of the interviewees, as well as because of the analysis method, which varies from one researcher to another (Hernández, Fernández & Batipsta, 2014). This analysis focuses on the opinion of experts in urban drainage systems and does not include other stakeholders who are also involved in the development of these systems. However, the wealth of information obtained through interviews provides results that help reflect and guide future research motivated by the answers of experts in the area. In addition, experience gives rise to the comparison of these opinions with those of other stakeholders related to urban drainage systems that future studies could carry out. Another limitation of this research lies in the size of the sample, which consists of a total of 11 respondents, which could be considered small. However, studies that have analyzed the opinion of experts to develop infrastructure systems have used comparable samples (e.g., n=7 [El Hattab, Theodoropoulos, Rong & Mijic, 2020]; n=6 [Hacker, Kaminsky, Faust, & Rauch, 2020]; n=12 [Uribe, Faust, & Charnitski, 2019]; n=15 [Araya & Vasquez, 2022]).

RESULTS AND DISCUSSION

This section discusses the results that provide answers to the three questions posed in the methodology: (1) What metrics could be used to evaluate the social sustainability of urban drainage systems?, (2) What barriers does the implementation of the identified metrics face? and (3) What modifications are proposed to the existing system?

The summary of the qualitative analysis results regarding the metrics that could be used to measure social sustainability in urban drainage systems is shown in Table 3. It presents the five categories that emerged in the information qualitative analysis process, with their respective subcategories.

The times each subcategory is mentioned in the interview answers (i.e., frequency) is indicated, as well as the number of interviewees that refer to this subcategory in their answers, which is shown in parentheses. These results reflect how aware the interviewees are of the possible metrics to evaluate social sustainability in urban drainage systems. For clarity purposes, the frequency of each subcategory is also shown in a percentage, which is expressed for each category, and the total of each category is expressed regarding the grand total. Again, the values in parentheses refer to the total number of interviewees; thus, 100% indicates that all interviewees mentioned the subcategory.

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Category	Subcategory	Frequency of responses (Interviewees)		Percentage value	
ENVIRONMENTAL BENEFIT	Water quality	7	(4)	23%	(36%)
	Amount of water	5	(5)	17%	(45%)
	Heat island effect	3	(3)	10%	(27%)
	Aquifer recharge	10	(8)	33%	(73%)
	Reuse of water resources	5	(4)	17%	(36%)
	Total	30	(11)	22%	(100%)
SOCIAL BENEFIT	Amenity, aesthetics, and community benefits	12	(7)	67%	(64%)
	Public information, education, and awareness-raising	6	(4)	33%	(36%)
	Total	18	(7)	13%	(64%)
SOCIAL EQUITY	Access to green areas	5	(4)	71%	(36%)
	Access to water	2	(2)	29%	(18%)
	Total	7	(5)	5%	(45%)
OBSTACLES	Availability of information	9	(6)	17%	(55%)
	Availability of resources	8	(6)	15%	(55%)
	Fragmentation of responsibilities	13	(5)	24%	(45%)
	Evaluation methodologies	14	(6)	26%	(55%)
	The rainwater paradigm	6	(3)	11%	(27%)
	Professional preparation	4	(3)	7%	(27%)
	Total	54	(11)	40%	(100%)
MODIFICATIONS	Global water entity	6	(4)	24%	(27%)
	Secondary standards	3	(1)	12%	(9%)
	Planning on a household scale	8	(5)	32%	(45%)
	Comprehensive valuation of benefits	8	(6)	32%	(55%)
	Total	25	(8)	19%	(73%)

Table 3. Frequency of responses on emerging categories. Source: Preparation by the authors.

BENEFICIOS SOCIALES EVALUADOS EN METODOLOGÍA MIDESO

- Menor daño en propiedades residenciales
- Recuperación en terrenos baldíos anegadizos
- Menor daño en propiedades comerciales e industriales
- Menor daño en establecimientos públicos
- Menor daño en vehículos
- Menor deterioro de la infraestructura vial
- Disminución de los costos generalizados de viaje
- Menores gastos de emergencia y limpieza de vías y sumideros
- Menor ausentismo laboral
- Menor ausentismo escolar
- Liberación de recursos públicos de salud
- Liberación de recursos públicos en ONEMI
- Beneficios no valorados

BENEFICIOS SOCIALES IDENTIFICADOS

- Calidad de agua
- Cantidad de agua
- Efecto isla de calor
- Recarga acuifero
- Reutilización recurso hídrico
- Amenidad, estética, y beneficios comunitarios
- Información publica, educación y sensibilización
- Acceso a áreas verdes
- Acceso al agua

Figure 3. Comparison between the social benefits currently considered and those obtained from the interviews conducted. Source: Preparation by the authors.

EVALUATION METRICS

On asking the interviewees about the benefits of sustainable drainage, 100% mentioned the environmental aspect, while 64% referred to the social aspect. This indicates that, within the expert group, there is less awareness of social benefits compared to environmental ones (Table 3). Similar results were obtained in Ferrans *et al*. (2022), where this lower awareness of social benefits is explained by the lack of research aimed at analyzing the social benefits of urban sustainable drainage systems.

On the other hand, the main environmental benefit mentioned by 73% of the interviewees is the contribution of aquifer recharge, which is understood as a benefit in possible water shortage scenarios. As for the social benefit, 64% highlight the aesthetic contribution of green areas in urban areas, defined as: "aesthetic and recreational elements, even spiritual ones, which mean coexisting more harmoniously with water within the city". These benefits are in line with two points of the SUDS design philosophy set out in its manual (Woods-Ballard *et al*., 2007), which are: protecting the water cycle and creating better spaces for people.

Regarding social sustainability, experts underline the role of social equality in terms of access to green areas and water. For example, one of the interviewees pointed out that: "There is a very large deficit of green areas in general in Chile, and these are also not homogeneously distributed throughout the country, both regionally and between regions." When analyzing figures of green areas per inhabitant indicators (i.e., m^2/inhab.) published in the cadaster of green areas of the INE (2018), the following values are noted: Arica (3.75), La Serena (11.01), Valparaíso (1.25), Talca (7.15), Valdivia (11.18). Within the Metropolitan Region, there are great differences between communes, for example, San Miguel (1.97) and Vitacura (18.67). The standard set by the National Urban Development Council is 10 (m^2/inhab.) and, according to their figures, only 15% of the communes meet this standard and 51% of the communes are below 5 m^2/inhab. (INE, 2018). It should not be forgotten that both equality in access to green areas, and the state of these, are fundamental for the community to make use of them and be benefited from them, to promote mental health and community life (Anthun *et al*., 2019).

The amenity, aesthetics, and community benefits suggest that drainage solutions not only have a socio-cultural component, but that also offer advantages often overlooked by institutions that are not associated with their hydraulic function, such as increasing the status and added value of neighborhoods. This is an aspect also evidenced by Ashley *et al*. (2018) in the United Kingdom, where people surveyed mentioned being willing to pay more for a home close to a green area generated for sustainable drainage.

Finally, given that the Chilean context is being analyzed, in Figure 3 it is possible to appreciate, on the left, the benefits that until today are contemplated in the social evaluation of rainwater drainage projects and, on the right, those identified through interviews. The comparison shows a gap between the current benefits and those discussed by experts. It can be seen that the list of existing benefits in the MIDESO methodology focuses on elements that are currently quantifiable, while the benefits obtained in this study may be difficult to quantify like, for example, amenity. However, it is considered relevant to highlight that the benefits identified in this work are not seen as benefits that should replace those in the current methodology, but as benefits that should be added to the existing ones. In this way, the importance of social sustainability in the development of sustainable urban drainage systems could be strengthened.

OBSTACLES

Regarding the difficulties detected by experts to apply social sustainability metrics, 45% of the interviewees highlighted the fragmentation of responsibilities between institutions, as indicated by one of them: "MOP (DOH) only has competence in the primary network, so it does not have the faculty to act at the local level. It would be ideal to start storing rainwater in houses, or on sidewalks before they reach the streets". This obstacle had already been identified in previous studies carried out in Chile (Patagua, Fundación Legado Chile and Pontificia Universidad Católica de Chile, 2021).

At a national level, an equivalent situation occurs, since there are basins located in more than one region, which implies that a coordination process is required between the DOHs of the regions involved, and also between the SERVIUs, which arises only from the goodwill of those in charge, but is usually lost when the department heads change, since "there is no organic system to do this coordination". Finally, the divided responsibilities hinder the delivery of solutions or the proposal of public spaces for comprehensive use or purpose, with the understanding that a public project can respond to multiple needs and not only to the role the agency that presents it has, as expressed by one interviewee: "there is a body concerned with a specific issue, this makes the work of the public sector difficult in general, the integrated view does not exist, it is spread in destination organisms." Something similar happens in Europe, where the different levels of action have been investigated, be it national, regional or local, and where policies and measures can be applied with the purpose of guaranteeing the path towards sustainable drainage (Gimenez, Breuste & Hof, 2020), which would be more efficient if implemented by a single body.

In the same vein, 55% mention specific evaluation methodologies, demonstrating that these hinder the realization of multisectoral projects. The methodology understands that an urban drainage project can only solve flooding problems, which are widely addressed by traditional systems, but leaves aside the benefit that a nature-based solution could provide in the social and environmental field. In this regard, one interviewee commented that "there is a lack of assessment methodologies that consider these aspects and that may not have been internalized. It is really important to approve projects and those numbers have to consider dimensions other than the economic one, like that associated with the environmental". The lack of methodologies is not a particular trait of the Chilean reality, but rather is found in several international diagnoses (e.g., Ashley *et al.*, 2018; Jimenez et al., 2019).

On the other hand, the current methodology does not consider the multiple needs that a project could cover, classifying it only in one function. Thus, for example, in the creation of a floodable park (i.e., Victor Jara Floodable Park in Santiago de Chile), the hydraulic dimension involved had to be evaluated using a rainwater and landscape methodology, through the cost-efficiency approach, as there is no methodology for this type of works, namely, the project was divided into two and was not evaluated comprehensively. Finally, the evaluation process is difficult because social sustainability metrics are difficult to monetize: "it is difficult to evaluate benefits, it is a global challenge. In the parks' aspect, it is possible to recognize those benefits, but it is very difficult to quantify them, putting them into numbers".

MODIFICATIONS

As a way to link and contextualize the results of this section, the modifications proposed by the interviewees are paired with the obstacles that these could impact (see Figure 3).

Household-scale planning and comprehensive benefit evaluation were the modifications most frequently referred to by the interviewees (Table 3). Household-scale planning proposes to develop techniques together with the communities, to avoid excessive runoff into primary networks. These initiatives have been applied in other countries: for example, in one Argentine locality, a specific flood problem was solved through sustainable drainage at the neighborhood scale (Villalba, Curto, Malegni & Linfante, 2019). This aims at projecting works with a lower cost and impact on the environment, with a consequent paradigm shift for professionals, who could consider the development of local rainwater management projects instead of carrying out works to deal with large design storms.

This work tries to promote an integrated valuation of benefits, which, among other aspects, proposes the creation of comprehensive assessment methods, which not only quantify the damages avoided by flooding but also the countless social benefits of SUDS, which might influence the projects that are to receive greater funding due to a greater quantification of their benefits.

The eventual creation of a global entity to manage sustainable urban drainage systems would mainly help to reduce the fragmentation of responsibilities in the management of rainwater systems. With this, monitoring conditions could be improved, more information would be available for decision-making, there would be a more efficient use of resources and, therefore, the availability of funds for other projects would increase.

CONCLUSION

In the study presented here, interviews were conducted with experts linked to the development of sustainable urban drainage systems in Chile. From their responses, we obtained (1) a group of metrics to measure the social sustainability of urban drainage systems; (2) information on the obstacles to the implementation of these metrics; and (3) suggestions for modifications to the current system for the sustainability assessment of urban drainage systems.

The main benefits identified by the experts were the contribution to aquifer recharge through the infiltration of rainwater, and the beautification of spaces with green areas. These benefits also have a direct impact on social equality, one of the aspects of social sustainability, since they directly relate to universal access to water and green areas. Regarding the obstacles to new metrics for evaluating the social sustainability of urban drainage systems, the fragmentation of the responsibilities of the institutions associated with the management of urban drainage systems stands out, along with the limited capacity of the current methodology to assess comprehensive urban drainage alternatives. In terms of the experts' suggestions to modify the current context, it is suggested to consider a comprehensive valorization of the benefits of urban drainage systems, an entity that addresses water resource management in a global and integrated way, as well as expanding the planning of water reuse at a household scale.

Finally, to strengthen the evaluation methodologies, it is recommended that subsequent studies look closer at the comprehensive valorization of social and environmental benefits, and focus on nurturing such methods with more complete and extensive databases.

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Abordando la sustentabilidad. La construcción del prototipo como herramienta proyectual docente
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ADDRESSING SUSTAINABILITY. CONSTRUCTION OF A PROTOTYPE AS A TEACHING DESIGN TOOL

ABORDANDO LA SUSTENTABILIDAD. LA CONSTRUCCIÓN DEL PROTOTIPO COMO HERRAMIENTA PROYECTUAL DOCENTE

Maria López de Asiaín-Alberich
Doctora en Arquitectura, Profesora Asociada, Grupo de Investigación Transhumancias: Arquitectura, Tecnología, Ciencia y Arte, HUM 965, Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, Sevilla, España
https://orcid.org/0000-0001-9422-394X
mlasiain@us.es

Miguel Hernández-Valencia
Doctor en Arquitectura, Profesor Contratado Doctor, Grupo de Investigación Transhumancias: Arquitectura, Tecnología, Ciencia y Arte, HUM 965, Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, Sevilla, España
https://orcid.org/0000-0002-3382-1097
mhvalencia@us.es

Jorge Roa-Fernández
Doctor en Arquitectura, Profesor Contratado Doctor, Grupo de Investigación Sath Sostenibilidad en Arquitectura, Tecnología y Patrimonio: Materialidad y Sistemas Constructivos, TEP206, Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, Sevilla, España
https://orcid.org/0000-0003-1254-3443
jroa@us.es

Rafael Herrera Limones
Doctor en Arquitectura, Profesor Contratado Doctor, Grupo de Investigación Transhumancias: Arquitectura, Tecnología, Ciencia y Arte, HUM 965, Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, Sevilla, España
https://orcid.org/0000-0001-9948-2019
herrera@us.es

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RESUMEN

Utilizar la construcción física de un prototipo como herramienta educativa no es una propuesta nueva, aunque puede ser innovadora en el contexto actual de renovación conceptual vinculado al desarrollo sustentable. En la Escuela de Arquitectura de Sevilla existe una gran tradición investigadora en materia de sustentabilidad, pero poco extrapolada a la enseñanza. También es necesaria una mejora significativa de la educación desde el ámbito metodológico. En este sentido, los concursos proporcionan una oportunidad que define una situación potencialmente afortunada para la innovación educativa. Partiendo de esta base, la presente investigación tiene como objetivo comprobar cómo la construcción de un prototipo a escala real, como estrategia metodológica educativa activa, de la mano de una metodología de diseño bioclimático consolidada en dicha escuela de arquitectura, permite lograr grandes resultados tanto en términos educativos como bioclimáticos. La metodología educativa empleada aúna las siguientes directrices: el taller como ámbito integrador para el aprendizaje arquitectónico; la construcción de un prototipo como situación educativa que trasciende lo arquitectónico; la conceptualización de los nuevos retos marcados por la sustentabilidad y su aplicación práctica y efectiva al proyecto, diseño y construcción arquitectónicos. Todas herramientas puestas en valor dan respuesta efectiva a las carencias actualmente detectadas e interiorizadas del aprendizaje-enseñanza y, por tanto, del quehacer arquitectónico.

Palabras clave
prototipos, aprendizaje activo, diseño arquitectónico, concurso.

ABSTRACT

Using the physical construction of a prototype as an educational tool is not new, although it can be innovative in the current context of conceptual renewal linked to sustainable development. At the School of Architecture of Seville, there is a great research tradition on sustainability, but little is extrapolated into teaching. There is also a need for a significant improvement in education from the methodological point of view. In this sense, competitions provide an opportunity that defines a potentially rewarding situation for educational innovation. From this starting point, this research aims at verifying how the construction of a full-scale prototype, as an active educational methodological strategy and following a bioclimatic design methodology consolidated in said School of Architecture, allows achieving great results both in educational and bioclimatic terms. The educational methodology brings together the following guidelines: the workshop as an integrating environment for architectural learning; the construction of a prototype as an educational situation that transcends the architectural; the conceptualization of new challenges marked by sustainability and their practical and effective application to the architectural project, design, and architectural construction. All the tools are valuable and effectively respond to shortcomings detected and internalized in teaching-learning, and, consequently, architectural activities.

Keywords
prototypes, active learning, architectural design, competition

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INTRODUCTION

ARCHITECTURAL DESIGN AND SUSTAINABILITY

Modern architecture education has been accompanied by multiple project design tools. Most of them are not new, although they are reinterpretations or reinventions of past experiments, which try to give value, once more, to approaches that allow responding to the current challenges and needs of architectural teaching. The start of this century has made the crisis of the architectural approach and profession evident. As professionals, we are not suitably responding to new challenges, we do not provide society with the service it needs, and architectural education and teaching must respond to this reality with vigor, change, reinvention, rigor, and, above all, a lot of enthusiasm.

The requirements that currently need to be addressed and faced are two-fold: conceptual and methodological. Indeed, on one hand, a conceptual revision of the architectural approach is essential (M. López de Asiaín, 2010), which involves reflecting on the current needs of society linked to sustainable development (ONU, 2015). On the other hand, it is also key to review and reintroduce teaching methodologies adapted to new educational profiles and the conceptualization of new approaches (Granero & García Alvarado, 2014).

Many tools have been designed and experimented with over the past century. However, an updated reinterpretation and adaptation are necessary, and therein lies the innovation of the process. The actual architectural design and construction process (Fernández Saiz, 2016) can be understood as one of research in itself, whose results and evaluations allow progression by testing, and understanding architecture as an experimental science despite the multiple potentially feasible methodological approaches (M. López de Asiaín, Echave & Fentanes, 2005). There have been numerous teaching innovation experiences carried out over the last decade at the School of Architecture of Seville (ETSAS) (Ramos Carranza, 2018). All of them involve a gradual and continuous effort to improve the teaching methodologies and tools teaching is approached with, aware of the need to review the educational strategy that motivates and generates knowledge transfer.

Sustainability in architecture, bioclimatic adaptation, or energy efficiency, are inescapable topics and concepts in this approach. However, the approach from different subjects and architectural knowledge, neatly cataloged and sometimes poorly related to the academic sphere, although fully interconnected, is methodologically diverse and enriching, so its integration into architectural projects is fundamental (Alba Dorado, 2019). In this sense, certain research strategies have encouraged collaboration and debate between areas of knowledge, subjects, and approaches, generating a climate that calls for change and improvement which numerous professors have leveraged, making interesting contributions (Herrera-Limones, 2013; Martínez Osorio, 2013). As an relevant example, during the experimental phase of the European project, *Educate* (Altomonte, 2009), workshops were held where several ETSAS professors participated (Blandón González, 2018; Blandón Gónzalez & Vallés Sisamón, 2019; Galán Marín, 2018; García Sáez, 2018; Pedreño Rojas, 2018; Rivera Gómez, 2018; Roa Fernández, 2018). There, the teaching projects of different subjects were worked on to incorporate specific environmental competencies, to ensure that students acquired the necessary skills to work from a sustainable development-based approach. In the same way, and from the same European research project, an experience linked to a European architecture competition for students was carried out.

Figure 1. Cover of the Educate Prize Publication.
Source: European Educate Project (EDUCATE Project Partners, 2012a)

The *Educate* Prize (M. López de Asiaín & Escobar, 2013) (Figures 1 and 2) proposed, as a challenge, a more sustainable habitat architectural intervention and proposal, designed in a location defined and chosen beforehand by the students. They had to be tutored by professors who had included environmental competencies in their teaching project and would use the *Educate* portal as a potential teaching tool (Cangelli et al., 2012). This portal included specific information and content

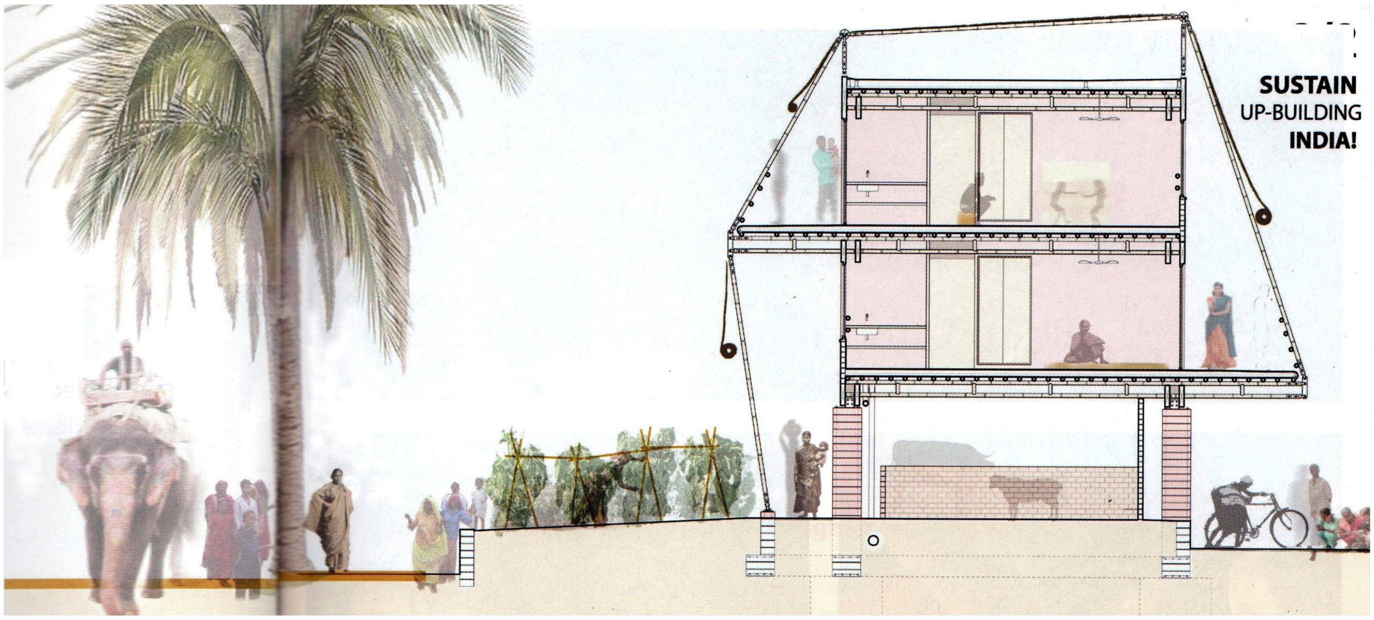

Figure 2. Project submitted to the Educate Prize. Source: European Educate Project (EDUCATE Project Partners, 2012a).

on the subject, from conceptual explanations and calculation guidelines, to design examples and even practical professionally developed and built examples. It also included communication tools, information, and debate among students, professors from all participating Schools of Architecture, researchers (Altomonte *et al.*, 2012) (more than 30), specialists in the field, and participants in the research project.

This experience proved conclusive in several respects. First, it showed that the interest of educators in incorporating environmental and sustainability matters in architecture teaching was real and, at the same time, an urgent need (*EDUCATE* Project Partners, 2012b). It was also confirmed that the rigorous doctrinal corpus on the subject was fully defined, completed, and accessible to both educators and students. And, finally, it showed that there was a great need to develop new teaching strategies and methodologies or reinterpretations, appropriate to the new transversal approaches and concepts that should be incorporated into teaching (Masseck, 2017).

It is worth mentioning that the School of Architecture of Seville has professors whose personal research backgrounds have been dedicated to the environment and sustainability in architecture and urbanism for decades. The oldest and most relevant case is that of Jaime López de Asiaín, who has incorporated environmental and bioclimatic analysis of buildings and urban spaces since the 80s (González Sandino & J. López de Asiaín, 1994) in architectural composition classes, within the framework of the Bioclimatic Architecture Seminar (Herrera-Limones, 2013). The analysis methodology he employs, subsequently defined and expanded (M. López de Asiaín, 2010) (Figures 3 and 4), is the foundation of professional and research architectural experimentation and, above all, the methodological and conceptual basis on which experimental case studies made during several investigations (González Sandino & J. López de Asiaín, 1994; J. López de Asiaín, 1997; J. López de Asiaín, 2001), as well as the present experience, are based. It is noteworthy to say that the approach this author develops combines architectural praxis with teaching and research, which allows the integration of the three dynamics and their feedback. It is difficult to determine the dynamic that incorporates, ahead of time, the bioclimatic and sustainability approach: the methodology of analysis of the types of architectural composition; the research on the hygrothermal behavior of a prototype for an Andalusian dry warm climate; the experimentation on a built case or the measurements made; and the extrapolation to other architectural projects of a larger nature. Therefore, these are analyzed as a whole to define the methodological strategy that feeds into this research.

Research and physical project experimentation are not only simulated but nurture and perfect teaching by reformulating analysis and decision-making methodologies. In turn, this teaching improves the professional practice, not only the personal but also the plural practice of the architect, by promoting the development of teamwork skills, fundamental nowadays, for all students, whether undergraduate, master's and/or doctoral, who subsequently put their bioclimatic capacity into practice in numerous projects (Figure 5).

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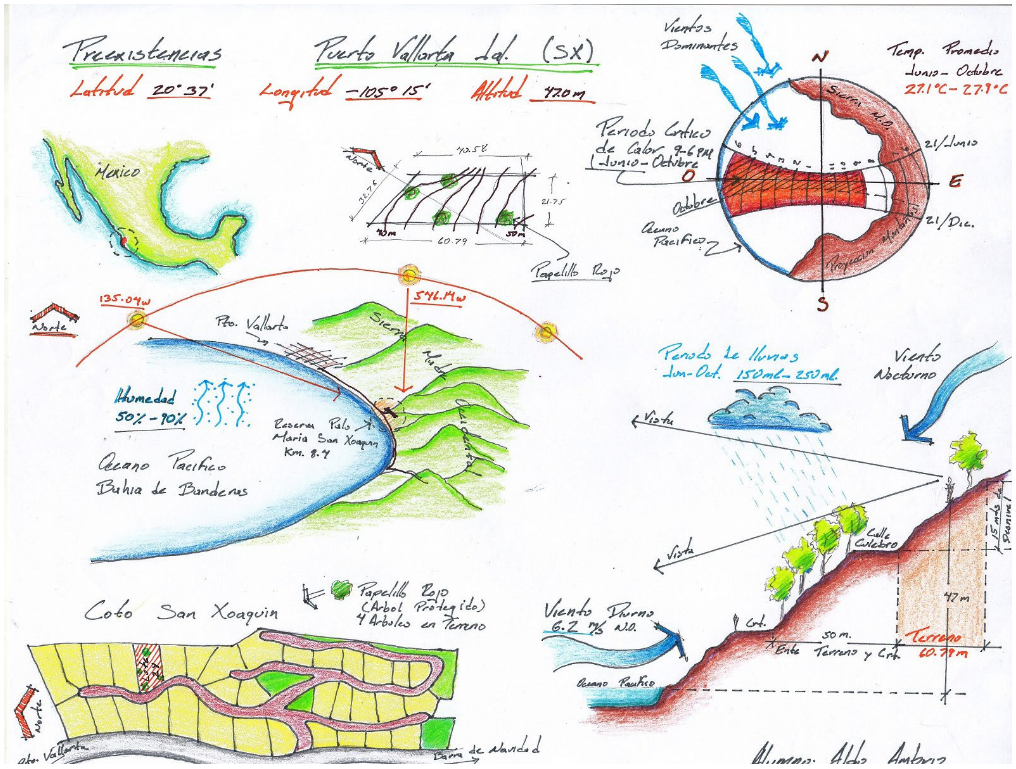

Figure 3. Methodological exercise of bioclimatic analysis. Corrections of the environment. Source: Student Aldo Ambriz.

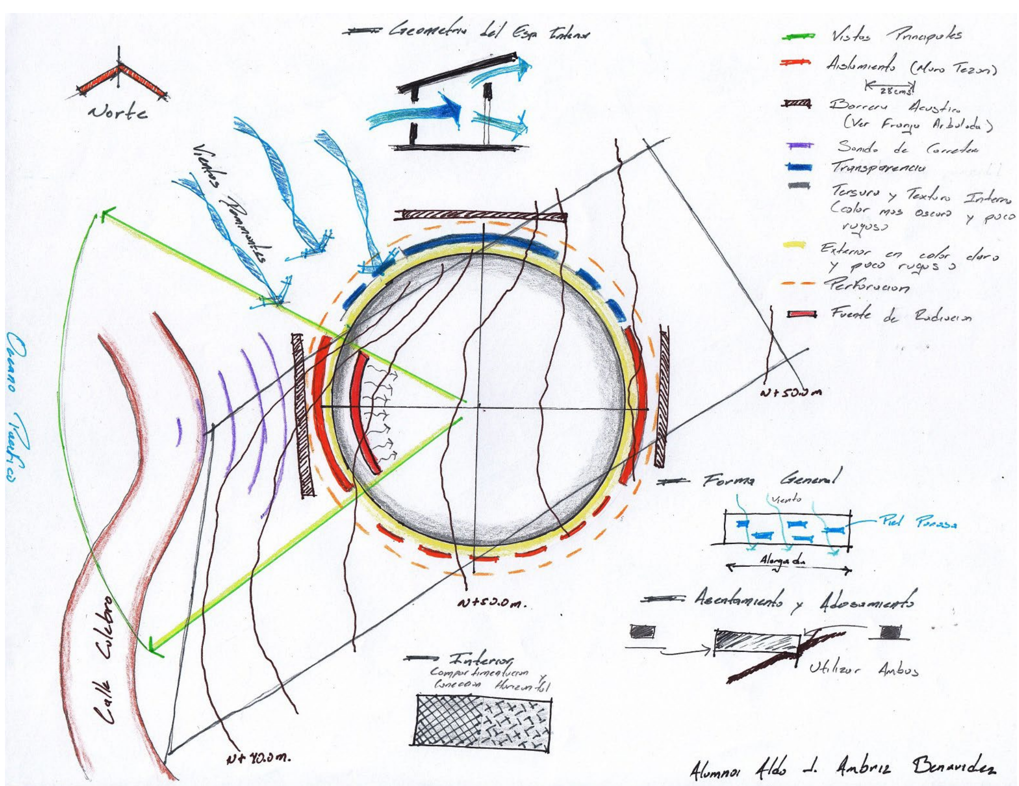

Figure 4. Methodological exercise of bioclimatic analysis. Bioclimatic analysis of the building. Source: Student Aldo Ambriz.

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Figure 5. Bioclimatic housing project in Mallorca.Source: Student Luis Velasco Roldán

RESEARCH- NETWORKING- PREVIOUS EXPERIENCES

The progress of research, in terms of sustainability in architectural project design, has been influenced and helped by international research networks. Renowned Seminars in the field in recent decades, such as those of PLEA (Passive and Low Energy Architecture[2]), have generated an international research support network without which the exchange of experiences, progress, and innovations made would not have been possible. For years, this network has provided contact between researchers from the School of Architecture of Seville and other European and Latin American universities that has allowed discussing, experimenting, and improving the gradual incorporation of research achievements into architectural teaching, both in terms of content and teaching methodology.

One of the experimental references used for the methodology employed in this research was the one performed at the School of Architecture and Design of the University of Colima 2012-2013 for complementary subjects of project design, habitat, and urban project (M. López de Asiaín &y Luna Montes, 2014). During these courses, several innovative approaches are used: the teaching program itself and its temporary intensification as an intensive workshop; the teaching methodology followed; and the bioclimatic and sustainability analysis methodology (Figure 6), transmitted to the students. Progress in this experience has later been incorporated and extrapolated to teaching at ETSAS in several subjects and, currently and to a large extent, constitute the basis of the teaching innovation processes of the authors.

Based on these experiences, a bioclimatic analysis and project design methodology are developed (Figure 7). The purpose of this study is to verify this bioclimatic analysis and project design methodology in terms of the educational experience, through the construction of a full-scale prototype in the context of the Solar Decathlon Europe 2019 Competition.

2 “PLEA is an organisation engaged in a worldwide discourse on sustainable architecture and urban design. It has a membership of several thousand professionals, academics, and students from over 40 countries. PLEA stands for “Passive and Low Energy Architecture”, a commitment to the development, documentation, and diffusion of the principles of bioclimatic design and the application of natural and innovative techniques for sustainable architecture and urban design. PLEA serves as an open, international, interdisciplinary forum to promote high-quality research, practice, and education in environmentally sustainable design. PLEA is an autonomous, non-profit association of individuals sharing the art, science, planning, and design of the built environment”. (Passive and Low Energy Architecture, 1982)

Figure 6. Concept of sustainability and habitability. Student work from the School of Architecture of Colima, Mexico. Source: Student Carlos Baltazar Ortiz.

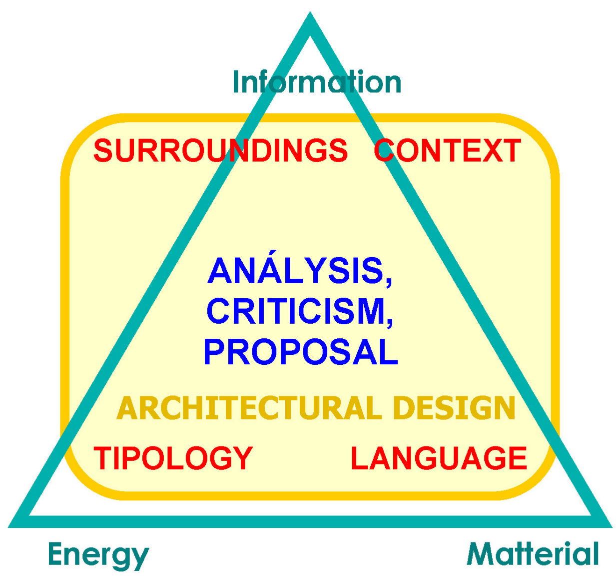

Figure 7. Outline of the project methodological process. Source: Preparation by the authors.

This bioclimatic design methodology, a synthesis of the broad, complex, and collaborative research process developed at ETSAS, following what has been expressed in the previous paragraphs, uses several consolidated tools. Some of them are solar geometry analysis (Serra Florensa & Coch Roura, 1995), and the psychrometric graphs of Victor Olgay (Olgyay, 1992), Baruch Givoni (Givoni, 1992), and Szokolay (Szokolay, 2008). It is also supported by several computer programs, such as Heliodón, Archisun, Design-Builder, or the unified Lider Calener Tool, used greatly in Spain.

To attain the objectives set out, this experience defines a necessary educational methodological process, based on active learning by projects, which is detailed below.

METHODOLOGY

The methodology used in this research focuses on the development of the following phases:

- Definition of an educational framework based on previous consolidated local experiences

and relevant international experiences, to incorporate sustainability in architecture teaching.
- Determination of the most suitable educational methodology and definition of specific variables that condition it and/or the educational methodological approach.
- Determination of the case study.
- Development of the educational experiment.
- Extraction of conclusions and learnings.

The educational methodological approach has three dimensions: the knowledge framework, based on the concept of sustainable development in all its breadth (environmental, social, and economic); the work methodology, focused on project-based learning (the student learns to learn); and the physical construction of the proposed prototype, as a materialization of the solved project and as an added problem to be solved by the students.

THE SOLAR DECATHLON COMPETITION AS A POTENTIAL FRAMEWORK

The Solar Decathlon 2019 Contest (Cobo-Fray & Montoya-Flórez, 2021) constitutes an optimal experimental framework for educational research (Chiuini, Grondzik, King, McGinley & Owens, 2013). It is run for several reasons:

- It incorporates, as a specific project proposal requirement, the environmental, social, and economic sustainability approach.
- In contrast to previous editions, urban aspects acquire greater importance and, thus, the urban approach incorporates the need to work from urban regeneration and social resilience.
- The competition's approach incorporates a multitude of transversal aspects complementary to the specific architectural one (M. López de Asiaín & Cuchi-Burgos, 2005), that force giving a broad response, beyond the architectural area itself[3].
- It is a competition by and for students, who are firstly responsible for their learning. Professors are incorporated as tutors and mediators on a secondary level, promoting more dynamic, practical, innovative, and educational teaching methodologies, from an approach based on the concept of sustainability.
- The competition's specific requirement, to build an experimental prototype, provides a suitable work framework and teaching research to check the objectives of the research presented.

Since its inception, the Solar Decathlon Competition has set out the bioclimatic and energy efficiency component as a core requirement of its proposals and the prototypes submitted for the competition had to comply with this. The fact that the prototype formulated as the competition's objective was always a single-family home, along with the North American urban planning tradition that prioritizes single-family housing over collective housing, has made it difficult to incorporate urban approaches that are more consistent with the paradigm of sustainable development.

RESULTS AND DISCUSSION

For the Higher Technical School of Architecture of Seville, the sustainability-based approach the contest has is a priority and is absolutely necessary in educational terms. This is why the participation of the University of Seville team is included, interpreting it in terms of educational research. It is only recently that the competition has begun to emphasize the relevance of urban aspects in terms of sustainability (Herrera-Limones et al., 2017), where educational research acquires meaning from a housing prototype-built urban habitat proposal (Figure 8).

On the other hand, the participation of the University of Seville's Solar Decathlon Team transcends the architectural sphere. The opportunity to work with students and professors from different Schools and areas provides a framework for transdisciplinary educational research (Moreno Toledano, 2017), compelling and relevant today. The team made an open invitation to the different Schools of the University of Seville to take part through their deans and, ultimately, the professors and/or researchers of the Schools of Mathematics, Physics, Medicine, Education Sciences, Communication, Psychology, Economics and Business, Fine Arts, Biology, the Office of Development Cooperation, the School of Computer Engineering, the Polytechnic or the Higher Building Engineering, took part in the 2019 project (Europe and Latin America-Caribbean) (Herrera-Limones et al., 2020). The experience is also enriched by the support of researchers from other universities, who are invited as experts during the contest.

3 The 10 items defined as goals for the Solar Decathlon are: architecture; engineering and construction; energy efficiency; communication and social awareness; urban integration and impact; innovation and viability; comfort conditions; housing operation; and energy balance (see: http://sde2019.hu/index_en.html).

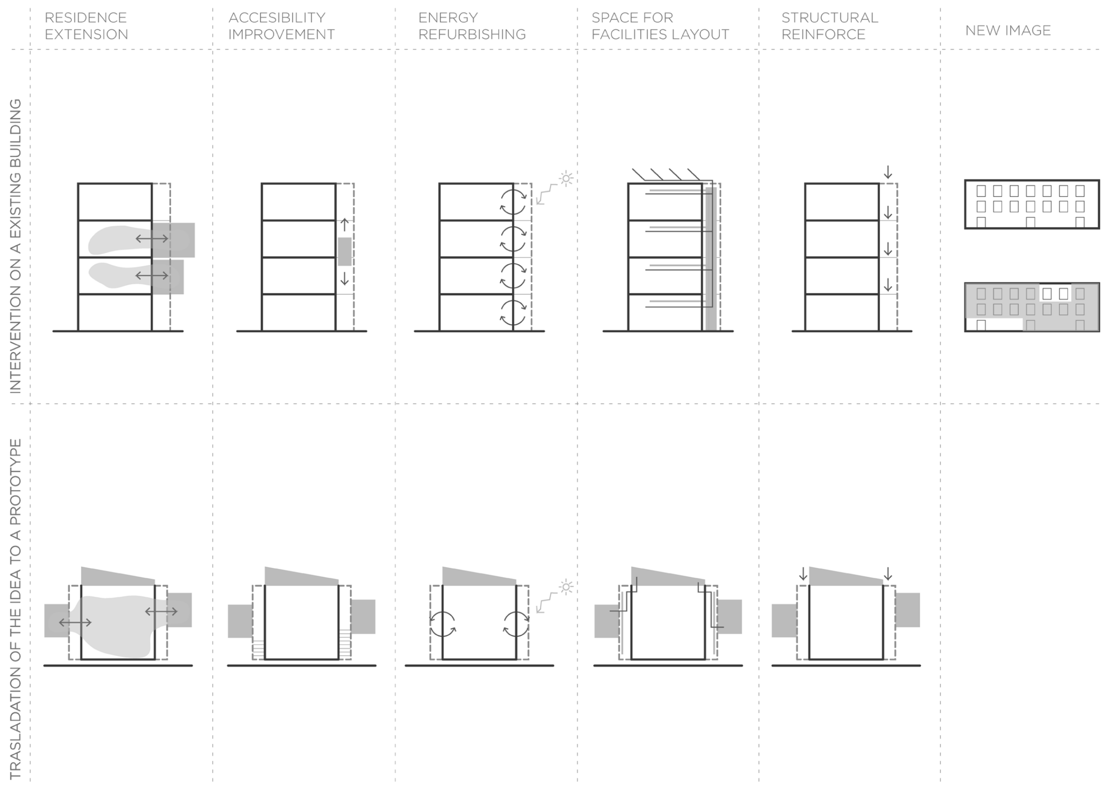

Figure 8. Outline of the "type" developed. Integration and urban conceptualization transferred to the architectural object. Source: Preparation by the authors.

Several teaching-innovation networks, currently active at the School of Architecture of Seville, also support the research project. Their methodological contributions are key. Other parallel investigations provide support to the proposed experimentation. This is the case of the University of Seville's Arus team, which works on the design and construction of racing car and motorcycle prototypes. The collaboration and exchange with this team allow, among other things, to progress and debate on more generic, but highly relevant matters considering the educational-methodological approach being applied, like logistics, management, the knowledge transfer between students of different courses, and student leadership, etc.

Along with the consolidation of the bioclimatic design methodology, a second objective within the framework of this research lies in defining and experimenting with the potential of the built prototype (Fernández Saiz, 2016), as a tool that incorporates the real professional world into teaching. In this way, the logistical, management, economic, and organizational aspects are part of the learning itself, apart from the purely disciplinary aspects linked to a more sustainable architectural design. Thus, numerous previous experiences in different contexts, accompanied by those mentioned at the Seville School of Architecture, have provided the base for the educational methodological approach applied here.

The definition of the 'type' or 'prototype' is an architectural educational exercise, whether academic, professional, or traditional, which allows searching and delving deeper into the project conception of the architectural object, verifying specific requirements (Figures 9 and 10). In this case, those established by the concept of sustainable development are chosen. In the same way, the suitability of the prototype model to its context, defined as a base requirement of the bioclimatic approach, is analyzed.

From the conceptualization, the methodology employed for architectural design based on a bioclimatic analysis of preexisting cases (Figure 9), ensures an environmental field in project design (Figure 10), while the social and economic requirements, studied from understanding and dialog, both with the market and with citizens and their specific needs, condition its final materialization decisions and construction definitions. The most relevant aspects considered, and the achievements attained, are detailed in Table 1. The project is laid out as a complex global problem to be solved and is approached from different perspectives and architectural requirements, problem by problem, decision by decision, understanding the process as a round trip that provides feedback as it moves forward, reflects, and faces crises step by step.

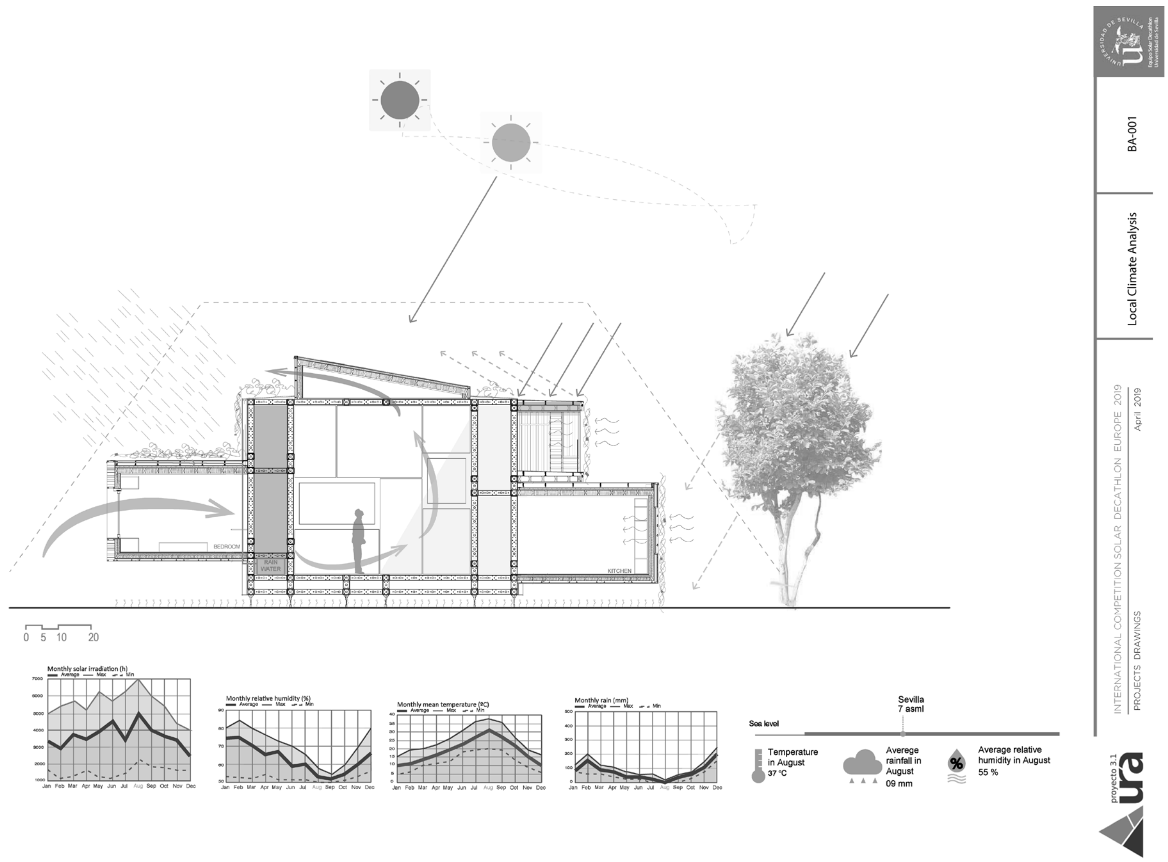

Figure 9. Outline of the bioclimatic analysis of pre-existences and prototype behavior. Source: Preparation by the authors.

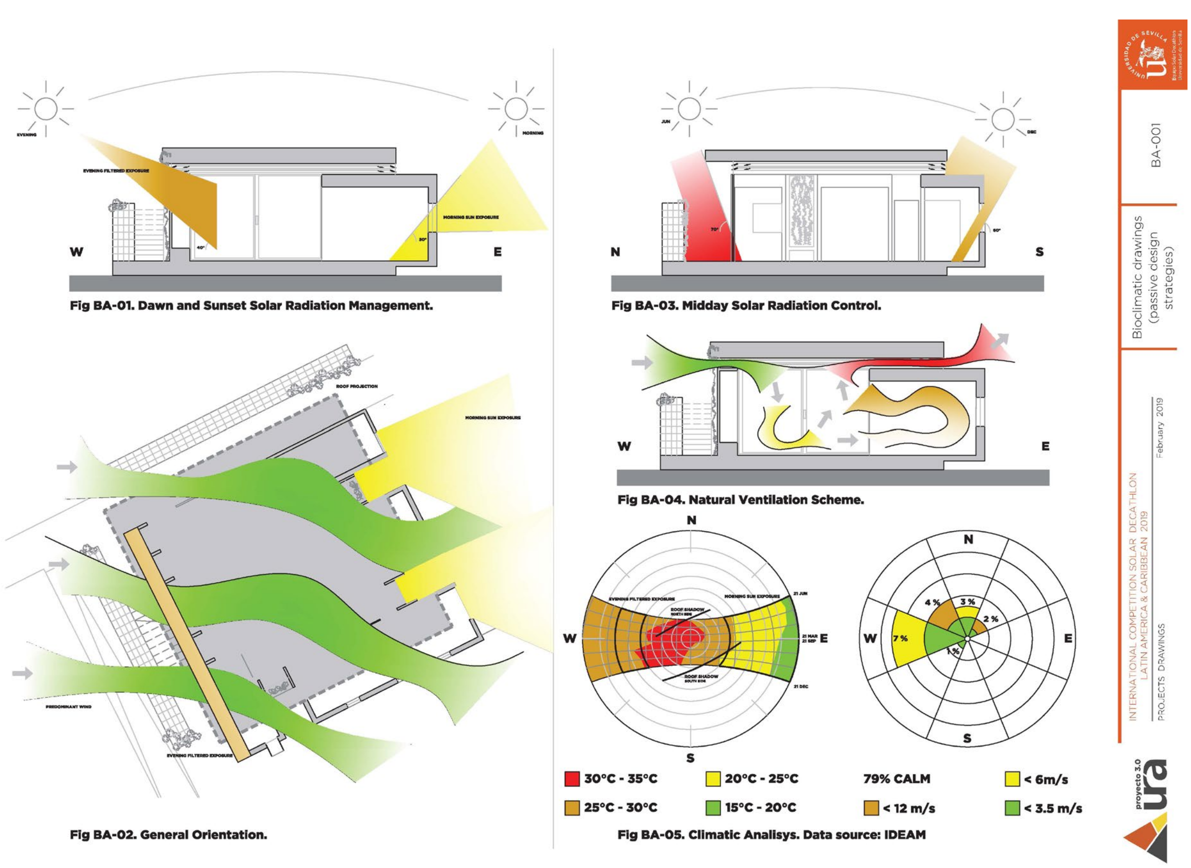

Figure 10. Bioclimatic behavior of the prototype. Source: Preparation by the authors.

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Economic sphere	
A "Low-Cost" prototype is made, that prioritizes the balance between resources consumed and results obtained.	
Social sphere	
The prototype is developed in the field of urban planning and management, based on the regeneration of an already built urban fabric, with certain characteristics of functional obsolescence and a high degree of energy poverty. Proposals for new building floorplans, that address the consumption and occupation of new unbuilt land, are avoided.	
The objective is to reduce, reuse, and recycle not only the waste generated but also the existing urban fabric.	
Environmental sphere (bioclimatic and ecological)	
Optimization of material resources	Within the framework of the "Low-Cost" concept, the use of recycled, rented, or borrowed products and systems is prioritized, to reduce the consumption of resources, emissions, and the energy consumed in the entire cycle. Studying light prefabrication systems allows controlling and reducing the amount of material involved and the emissions derived from the building process.
Reduction of energy consumption through passive strategies and the promotion of renewable energies	The use of passive and capture systems is prioritized to use natural energies and the dominant air currents of the environment. Cross ventilation, a central patio, atomization of the spaces to facilitate their control, daylighting, double skin, solar control, and correct orientation are used. High-efficiency thermal insulation is used throughout the envelope to avoid thermal bridges, with controlled ventilation to improve indoor air quality and guarantee internal comfort. Simulations are carried out to specifically optimize the choice and use of high-performance active lighting and conditioning systems and equipment.
Reduction of waste and emissions	In the construction, priority is given to the use of recycled or rented materials and systems in the structure, in the enclosures, furniture, facilities, and products that have a second useful life and can be remanufactured in other construction processes. The use of prefabricated systems facilitates the subsequent reuse and assembly in other projects. The use of internal recycling systems for rainwater, gray water, and waste generated in the construction itself is also studied.
Decrease in the maintenance, operation, and use of buildings	An exhaustive study of the parts of the prototype is made considering their life cycle, maximizing the so-called "three Rs" (reduce-reuse-recycle). Some parts used for the prototype construction are rented or borrowed, and others, after the competition, are sold for their reuse. The prototype is designed based on a surface and durability consistent with the contest's exhibition. However, in the continuous monitoring of its service life cycle, once the exhibition is over a large part of the prototype is sold to a Hungarian citizen. This makes it possible to extend the service life of these modules and save transport resources.
Improvement of the quality of life of the building's occupants	The study of the prototype's internal comfort is one of the pillars of previous studies based on natural ventilation, a flexible functionality, perfectible, and adapted to the needs of new family models. A balance is achieved between the use of domestic automation systems that integrate all these functions and optimize overall energy consumption, with the incorporation of passive devices to regulate comfort (temperature, air movement, and adequate indoor humidity), in addition to a specific use of active support systems.

Table 1. Sustainability aspects addressed in the study and construction of the prototype. Source: Preparation by the authors.

In the construction area, the tradition maintained by Bauhaus regarding the trade as an essential and primary part of the architect's training is recovered (Ramos Carranza, 2010), the workshop being the space required to initially prepare the project and, subsequently, for its constructive development. The physical construction of the prototype (Fernández Saiz, 2016) is an educational opportunity of special relevance (Figure 11) since it forces students to face numerous challenges that, otherwise, would not be easy to raise. Firstly, time management related to onsite management of different agents; second, the necessary decision-making, both constructive and structural, since the prototype 'has to be built'; third, the production of information needed to build the prototype regarding planimetry, and; fourth, the management and use of team dynamics.

The time management of the work is key, as the work unit depends on this and conditions progress. To this end, coordination in decision making, planimetry production, financial management for the supply of materials, and the construction itself, which includes managing work

Figure 11. Beginning the prototype's construction. Source: Preparation by the authors.
Figure 12. Implementation of the prototype in the final location. Source: Preparation by the authors.

safety, is vital. Architecture students usually have a very vague idea of the complexity of these processes, and experiencing them allows them to get involved in their real resolution and enhances construction processes, compared to the design processes they are more familiar with.

In addition, the construction process forces them to delve into the constructive design of the project and make decisions they are not normally forced to make. Facing a worksite requires designing by deciding on a larger scale than usual, and solving problems that occur during the construction process (Figure 12) that, probably, in purely academic projects, would be discarded as "irrelevant". This also requires defining and producing a very detailed and clearly expressed planimetry for its use by third parties, who may not be designers or students.

This resolutive overexertion provides them with a remarkable capacity for reaction and work. Team management and the use of its maximum potential by combining efforts (Figure 13) is, perhaps, one of the most valuable lessons that can be acquired, although it is not simple and should be based on the simultaneity of integrated knowledge learning (Domingo Santos, 2010). Students are normally used to working in groups, next to each other, but in a sequential, non-integrated way, which is necessary when approaching collaboration from a holistic approach. An integrated prototype design for the Solar Decathlon competition requires and promotes holistic versus sequential and even traditional collaboration in the peer-to-peer architectural profession (whether architects or engineers), in charge of different aspects of a project (structures, construction, installations), just as Chiuini *et al.* (2013) state. The experience that this competition entails during the construction phase, in this sense, is of great importance, albeit basic, due to the limited maturation times for the team, which would always demand more opportunities for collective and cooperative learning.

Figure 13. Completion of the prototype in Hungary.Source: Preparation by the authors.

This methodological approach is a pedagogical experiment like the one developed in Amereida, Open City, Chile (Millán-Millán, 2019), which starts from the methodological principles of Bauhaus and combines theoretical conceptual reflection and the real practice of the architectural project. The constructive experience is considered a life experience, not just an educational one, because of its implications in the person's training and not only in that of the technician. When students face the priority, urgent, and rigorous technical issues involved in building a prototype, from a decision-making process that many must agree upon - not decided by teachers or a particular student -, the constructive exercise entails a collaborative life experience (Figure 13).

The work is accompanied by numerous planimetry adapted to each phase of the construction process. The models (Figure 14) are also a fundamental tool in the project's incremental development, adapting in scale to decision-making from the urban, architectural, and, subsequently, the constructive fields. The prototype is mostly made in

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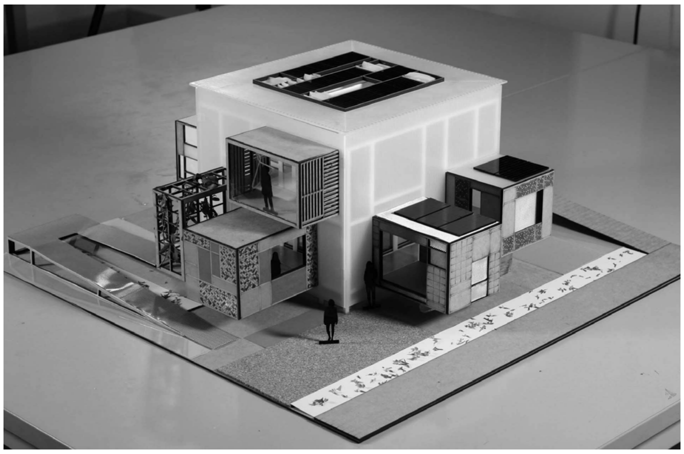

Figure 14. Solar Decathlon Europe prototype model. University of Seville team (2019). Source: Preparation by the authors.

Seville and then moved to the competition site, where its manufacture is finished. This in-depth collaborative research process, that starts from the design and acquires meaning with the construction by the students, is an educational experience rarely reproduced in all its experiential complexity at the School of Architecture of Seville.

The AURA 3.1 prototype was developed for the Solar Decathlon Europe 2019 competition (Herrera-Limones et al., 2021). The project, which we call the AURA Strategy, was based on a sustainable construction strategy for the urban regeneration of obsolete residential neighborhoods, through the reuse of existing buildings, while taking into account the Mediterranean climate. The neighborhood of the San Pablo Industrial Estate in Seville (Spain) was chosen as a case study for the project's urban application.

The effectiveness of the proposal in terms of sustainability was demonstrated by the results of the competition. It obtained the first two prizes in the quantitative tests, based on the onsite measurements collected with sensors installed on the prototype: Comfort and Operating Conditions of the House (Alonso, Calama, Suárez, León & Hernández, 2022). In addition, it won a third prize in the Sustainability competition, which proves the enormous possibilities that the AURA Strategy has in the field of sustainable urban regeneration and bioclimatic behavior in social housing retrofitting.

The main regenerative action applied consisted in the juxtaposition, on a social housing block, of a technological-structural system that provides new technological and spatial features. This prefabricated system is composed of a connecting envelope and expansion modules with the following features: a fragmented system that allows a more generalized application on a greater number of housing units and the ability to adapt to the specific requirements of each building/dwelling; a progressive system that does not require a full building to be operational; a system compatible with the use of the building during the construction process; and a system open to the incorporation of future needs.

The achievements obtained in the competition have allowed continuing with perfecting the possibilities of the proposal, through the research project entitled "Direct application of the *Aura Strategy* of the U.S. Solar Decathlon Team, in the rehabilitation of obsolete Andalusian slums", funded by the Junta de Andalucía (Spain) and currently under development.

CONCLUSION

The validity of the process compared to the pure finalist nature of this type of teaching project strategy, the wealth of the countless borderline situations raised on the road, as well as two-way learning between professors and students, make this type of experience an excellent teaching tool in the field of the sustainable social habitat, given that the bioclimatic aspects of ideation, project, and prototype implementation are especially valuable.

This unique form of research (using project instruments and architectural construction with a prototype specifically conceived for each case in question) requires previous theoretical inquiry about what the new types of more sustainable construction systems and the most environmentally efficient housing solutions could be.

In short, the educational methodology used is confirmed as strategic for obtaining timely results that train the student within a sustainability framework. The active methodology of project-based learning has the student face a specific problem, supported by their professors and the existing doctrinal body on the subject, but one which they need to address together with their peers, in a proactive, coordinated, and resolutive way.

Thus, the strategy of building a prototype and not just its design with bioclimatic criteria is an added challenge, as it involves aspects of the architectural area (especially development and construction logistics) that go beyond the project itself, and that are linked to its physical concretion, an experience that students do not usually face. From that perspective, the achievements obtained in terms of bioclimatic design efficiency (proven by the prizes won, and not just for the simulations made), materialization, and final construction (real constructive definition), but also in the approach to a complex reality (organizational and logistical feasibility), are multiple.

Specifically, the Solar Decathlon competition has become the ideal framework for this educational experiment of incorporating sustainability aspects. (Chiuini et al., 2013) thanks to its specific requirements. The students, decathletes for the competition, together with the

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professors and researchers who mentor and support them, have formed a design and construction team that experiences the educational process through the project work and problem-solving methodology. The University of Seville, which has been taking part assiduously in the competition since 2010, has closed (for the moment) its participation in this type of competition with the 'Aura 3.1' project, built in Budapest, Hungary, in July 2019, in the last edition held in Europe.

The results obtained allow confirming that the educational approach and methodology employed are suitable for incorporating sustainability issues in architecture teaching, not only from a theoretical point of view but also from a practical one. Indeed, the entire project represents a significant advance in knowledge transfer, but above all, skills and abilities for architecture students. This is complemented by other types of teamwork skills, which although not specifically architectural, do strengthen aspects of sustainability linked to cooperation and collaboration, essential in its social sphere.

The active methodological dynamic, based on project solving, was adapted to the corresponding times and management, posing the different phases of progress in the design as problems to be solved among participating students, from the different subjects involved in the research project. In this way, the professors acted as mentors of the students' research, helping to define the objectives and goals to be achieved.

The participation of students from different areas (architects, engineers, journalists, communicators, translators) constituted a complex management factor, but a clear learning improvement. It made it possible to holistically address the challenges defined by the competition from the global aspect, confirming the complexity of the architectural-constructive process, beyond the architectural area itself, and providing students with an experiential approach to this reality, that will sharpen their collaborative capacity. In the same way, the experience became a transversal experiment (Masseck, 2017) within architecture, where the need to work on the constructive complexity of a project beyond its design and formal resolution becomes clear. With this, it was possible to introduce students to the integrated dynamics involved in the constructive definition of a built project (Alba Dorado, 2019), which meant them physically facing the need to constructively materialize a design (Fernández Saiz, 2016), and ensure its correct final operation.

However, the methodological dynamic, which in its approach has been confirmed to be suitable and very productive, has lacked rigor in its application and there is potential room for improvement. Some improvement proposals should focus on greater involvement of students in the leadership and management of the process itself. It is possible and desirable that they take on greater responsibility in decision-making, not only in the design but in its management and the prototype's construction process. It is also necessary to work on involving more students by better dissemination of activities within the university. Numerous areas, that did not take part, can be brought into the project and enrich it as a collective educational experience.

On the part of academia, it is essential to make an effort from academic management that allows student participation without impairing their productivity and academic results in the subjects of the different courses. The learning that the experience of participating in this type of competition provides, does not increase the student's academic rigor, but simply varies the methodology of acquiring knowledge, that must be fully and clearly recognized by the different subjects involved. From this approach, it is necessary to define evaluation tools that allow assessing the knowledge acquired by each one of the participating students, so that the experience constitutes a possible educational path linked to obtaining a degree in architecture or even opening the door to a master's degree program.

This experience undoubtedly highlights the educational capacity that a prototype design and physical construction process can mean for a student. Contact with the constructive reality contributes to accelerating the architectural maturation process and taking onboard the knowledge they acquire linked to each architectural area. The methodology involved allows experiencing collaborative and cooperative processes that their future work will demand, and to get to know their potentialities and weaknesses in terms of team management, working with peers, and with other areas. Today, all these skills are key for professional architectural work, so the strategy implemented is considered a success.

Finally, the incorporation of the sustainability paradigm in architecture teaching finds, in this experience, a solid basis for development that concretizes the efforts previously made by the School of Architecture of Seville. Its environmental path, which began with the Bioclimatic Architecture Workshop, is now crystalized with this kind of experience, supported by a line of research in sustainable habitat involving numerous groups, which is responsible, in turn, for ensuring the connection between the different areas that sustainability has brought together in recent years, given the urgency of climate change and the Framework of the Sustainable Development Goals.

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OPTIMIZATION OF CLASSROOM DESIGN: USE OF NATURAL LIGHT FOR VISUAL COMFORT IN VILLA MARÍA, ARGENTINA[1]

OPTIMIZACIÓN DEL DISEÑO DE AULAS: APROVECHAMIENTO DE LA LUZ NATURAL PARA CONFORT VISUAL EN VILLA MARÍA, ARGENTINA

David Salomón
Arquitecto, Proyectista, Secretaría de Planificación Técnica, Servicios y Mantenimiento, Universidad de Villa María (UNVM), Córdoba, Argentina
https://orcid.org/0000-0003-4029-7737
arqdavidsalomon@gmail.com

Sofia Avalos Ambroggio
Arquitecta, Docente de Cátedra, Facultad de Arquitectura Urbanismo y Diseño (FAUD-UNC), Universidad Nacional de Córdoba, Córdoba, Argentina
https://orcid.org/0000-0002-1520-5389
sofia.avalos@unc.edu.ar

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RESUMEN

El presente trabajo aborda la problemática de la iluminación natural en edificios educativos, enfocándose en el estudio de estrategias de iluminación natural que contribuyan a alcanzar niveles recomendados de confort lumínico dentro de las aulas, correcta distribución de luz y reducción de deslumbramiento. Se analizó, en ese marco, un edificio del campus de la Universidad Nacional de Villa María, Córdoba, Argentina, en el que se evaluó el comportamiento de iluminación natural usando modelos de simulación y mediciones *in situ*. La labor se complementó evaluando el índice Daylight Glare Probability (DGP): verificando ocurrencia de deslumbramiento. El diagnóstico mostró exceso de iluminación en puntos cercanos a aberturas, iluminación insuficiente en puntos lejanos a las mismas, niveles bajos de uniformidad en la distribución de iluminación natural y umbrales intolerables de deslumbramiento. Consiguientemente, se propuso un nuevo ordenamiento del aula, incorporando elementos para la redirección de la luz solar y se verificó su desempeño. Los resultados de la propuesta evidenciaron importantes diferencias. Se consiguió una importante reducción de niveles de iluminación, alcanzando niveles de confort visual para aulas (300-500 lux promedio), mejoras en la uniformidad de luz natural, con su consecuente verificación según los estándares y una reducción significativa de niveles de deslumbramiento por penetración solar directa.

Palabras clave
iluminación natural, confort visual, deslumbramiento, edificios educativos.

ABSTRACT

The present work addresses the problem of natural lighting in educational buildings, focusing on the study of natural lighting strategies that contribute to reaching recommended levels of lighting comfort in classrooms, correct light distribution and glare reduction. In this framework, a building on the campus of the National University of Villa María, Córdoba, Argentina, was analyzed in which the behavior of natural lighting was evaluated using simulation models and in situ measurements. The work was complemented by evaluating the Daylight Glare Probability (DGP) index: verifying the occurrence of glare. The diagnosis showed excess lighting at points close to openings, insufficient lighting at points far from them, low levels of uniformity in the distribution of natural lighting and intolerable glare thresholds. Consequently, a new arrangement of the classroom was proposed, incorporating elements for the redirection of sunlight and its performance was verified. The results of the proposal showed important differences. A significant reduction in lighting levels was achieved, reaching levels of visual comfort for classrooms (300-500 average lux), improvements in the uniformity of natural light, with its consequent verification according to standards, and a significant reduction in glare levels due to penetration direct sun.

Keywords
use and management, occupancy, occupant behavior, thermal comfort, bioclimatic strategies

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INTRODUCTION

The possibility of accessing daylight inside educational buildings is considered one of the most determining physical characteristics of a classroom (Phillips, 1997). Numerous authors agree that quality daylighting inside educational spaces not only favors the comfort of its occupants but also has a direct impact on teaching and learning activities, as well as on the academic performance of students (Gonzalo, Ledesma, Nota & Márquez, 2001; Heschong, Wright & Okura, 2013; Robles Machuca, 2014, among others). Meanwhile, the absence of quality daylighting can cause fatigue and psychophysical stress, affecting people's moods (Muñoz Núñez, 2010). It follows, then, that light conditioning, which includes quality daylighting in spaces intended for education, is a fundamentally important requirement.

In Argentina, the IRAM-AADL Standards constitute the regulatory framework of recommendations for energy efficiency and light comfort in institutional buildings. Law N°19587 on Health and Safety in the Workplace, regulated by Decree N° 351/79 (Chapter 12 "Lighting and Color", Articles 71 to 84, and Addendum IV), includes requirements for minimum lighting values tabulated in the IRAM AADL J20-06 (2017) Standard and establishes calculation procedures for average illuminance and lighting uniformity, together with admissible values. Likewise, the Superintendency of Occupational Hazards (SRT, in Spanish), of the Ministry of Labor, Employment, and Social Security, outlines procedures for measuring lighting in built spaces (SRT Resolution 84/2012).

However, the regulations and protocols on this issue are limited. The IRAM-AADL Standards are for guidance only and their application is voluntary, and there is no official body that checks the compliance with the requirements of Law 19.587. In this way, the objective of including design premises and strategies for lighting comfort falls on the will of professional design teams. The literature on the subject points out that, during the development stage of a project, designers must determine availability parameters and the selection of appropriate daylight data that will be used as a basis in the design proposal (Gonzalo *et al.*, 2001; Pattini, 2000). Nevertheless, there are few planning teams in charge of developing educational building projects that have suitable tools, with an established procedure to simulate the behavior of daylighting-associated indicators or specialized consultancies on the subject, so it is very difficult to foresee the future performance of the projected building.

As a result, many buildings have problems of little or no daylight penetration during working hours or even have excessive penetration of sunlight and glare issues. This leads to seeking ways to counteract the negative effects, often by using interior curtains that block the entry of daylight, or by complementing the lack of light with artificial lighting during daytime hours, which throws away the benefits of daylighting and increases the energy consumption of the building.

This study was carried out jointly with the Secretariat of Technical Planning, Services, and Maintenance of the University of Villa María, Córdoba, Argentina. The objective is to analyze the performance of an educational building and propose improvement alternatives to achieve the recommended levels of light comfort inside classrooms, incorporating passive solar energy strategies.

DAYLIGHTING IN EDUCATIONAL BUILDINGS

Both light comfort standards and the proposal of design recommendations to incorporate daylight in educational buildings have been the subject of study by different institutes and research organizations. In Chile, the Chilean Energy Efficiency Agency (AChEE, in Spanish) developed the Energy Efficiency Guide for Educational Establishments, *GEEEduc* (CITEC-UBB, 2012), which includes design strategies for the incorporation of daylight in educational spaces and recommendations to achieve visual comfort inside classrooms. Likewise, Piderit & Bodart (2012) propose design criteria for classroom organization, establishing areas with different lighting requirements. In the same vein, other studies present design strategies to optimize daylight in offices (Piderit & Bodart, 2012; Palarino & Piderit, 2020) and classrooms (Callejas, Pereira, Torres &Piderit, 2020).

In Argentina, the Infrastructure Directorate of the National Ministry of Education (DIMEN, in Spanish) establishes conditions and requirements for habitability in school buildings in the document "Basic Criteria and Regulations of School Architecture" (DIMEN, 1998). One of the basic objectives of building design focuses on "ensuring daylight and ventilation conditions as the main solution" (DIMEN, 1998, p. 57). This document proposes design strategies in terms of recommended orientations and dimensioning of openings. There are also several studies on the use of daylighting in buildings, some focused on the re-functionalization of built workspaces, whether classrooms or offices, using daylight (Ferrón, Pattini & Lara, 2010); classroom design strategies (Pattini,

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Indicator	Ranges					
Mean illuminance (lux)	Insufficient	Deficient	Recommended	Excess light	Discomfort	[1]
	< 200	200 - 300	500 - 750	2000 - 5000	> 5000	
Uniformity of illuminance	Insufficient	Deficient	Acceptable	Good	Required	[2]
	< 0.2	0.2 - 0.3	0.3 - 0.4	0.04 - 0.05	> 0.5	
Glare (DGP) (%)	Imperceptible	Perceptible	Bothersome	Intolerable		[3]
	DGP < 34%	34% <DGP< 38%	38%<DGP<45%	45% < DGP		

Table 1. Daylighting indicators considered in this work. Source: Preparation by the authors based on [1] Callejas et al., (2020); Decree No. 351/79, DIMEN (1998); [2] Callejas et al. (2020); Decree No. 351/79; [3] Wienold and Christofferen (2006).

2009; Cisterna *et al*, 2015), controlling lighting levels and daylight distribution in classrooms (Hoses, San Juan, Melchiori & Viegas, 2001; Pattini & Kirschbaum, 2006); opening protection devices to avoid direct solar radiation (Ledesma *et al*., 2004; 2005, Monteoliva, Villalba & Pattini, 2014); the use of light trays (Gonzalo *et al*., 2001; Casabianca & Evans, 2003), and glare control (Pattini *et al*., 2009).

DAYLIGHTING INDICATORS

Daylighting of indoor work or reading spaces should be diffuse, uniform, and have low contrast indices (Pattini *et al*., 2009). The illuminance level (E) refers to the amount of luminous flow emitted by light sources, and that vertically or horizontally reach the surfaces (Robles Machuca, 2014). The indicator proposed by the Protocol of SRT Resolution 84/2012 to measure Illuminance is Mean Illuminance (Em). This protocol also proposes calculating the Uniformity of illuminance (U). This indicator complements illuminance analysis since it makes it possible to detect situations where the average for the mean Illuminance value masks horizontal illuminances below the acceptable value (Pattini *et al*., 2009). Educational spaces require a suitable level of illuminance to ensure a relatively high uniformity of illumination (U) in the work area.

Glare is one of the most influential indicators of visual comfort (Monteoliva, Garretón, & Pattini, 2021). The Daylight Glare Probability (DGP) prediction model, developed by Wienold and Christofferen (2006), is considered one of the most accurate models for studying glare inside built spaces. It is defined as the probability of visual discomfort perceived by an occupant, due to differences between very dark and very bright areas, caused by direct solar penetration of a light source or excess lighting levels in an indoor environment (Palarino & Piderit, 2020). The permissible ranges of mean illuminance, daylight uniformity, and DPG are summarized in Table 1.

METHODOLOGY

Currently, the National University of Villa María (UNVM) is immersed in the transformation process of its campus, following the guidelines of the "Towards a Sustainable University City" Program (UNVM, 2019), which includes a strategic development master plan, the "UNVM Infrastructure Master Plan 2020-2021", led by the Secretariat of Planning, Technical, Services, and Maintenance (SPTSyM, in Spanish). One of the Program's goals is "to get to know and analyze the physical conditions and comfort levels presented by the buildings built on campus, to propose interventions that help improve working conditions in classrooms." (SPTSyM, 2020, p. 17). In this context, this work proposes evaluating the classrooms of one of the buildings to verify the daylighting indicators and propose improvement alternatives. The methodology used in this study (Figure 1) is presented below.

1. SELECTION OF THE CASE STUDY

A classroom was chosen that met the following criteria: 1. A classroom whose assessment was required within the SPTSyM Infrastructure Master Plan; and 2. A classroom that was considered as "standard", in the sense that the results of the evaluation could be extrapolated to other classrooms.

Following this, a building was chosen, "Institutos II- Rector Carlos Domínguez", which was originally

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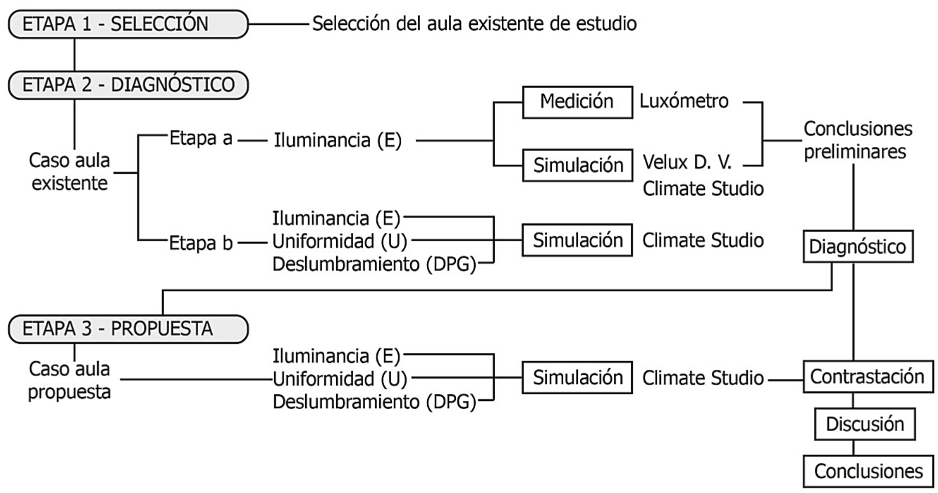

Figure. 1: Proposed methodology. Source: Preparation by the authors.

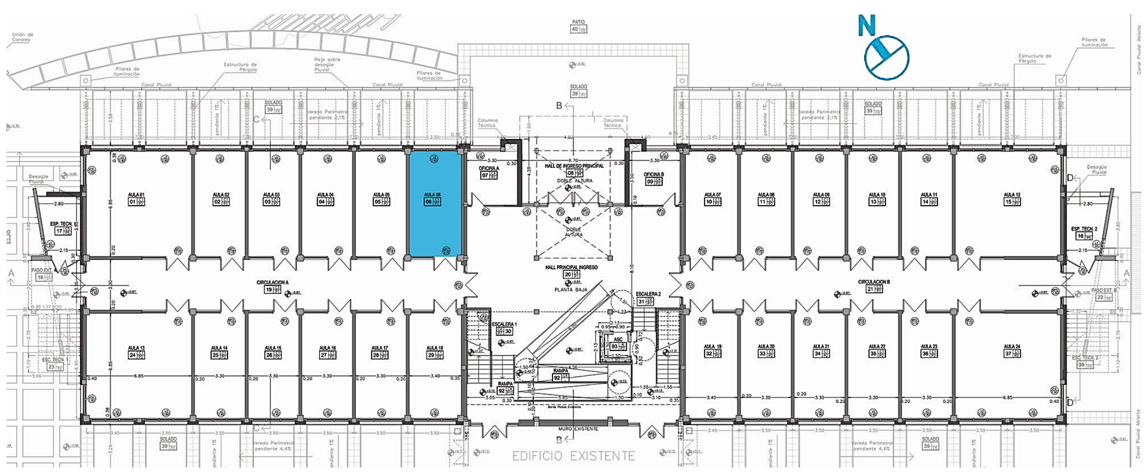

Figure 2: Selected classroom. Ground floor of the building “Institutos II”, UNVM. Source: Technical file of the building “Institutes II”, SPTSyM, UNVM.

Figure 3. Selected classroom. a) Interior view at the back of the classroom. b) Interior view to the front of the classroom. c) Interior view with closed curtains. d) Exterior view of the classroom - north facade. Source: Preparation by the authors.

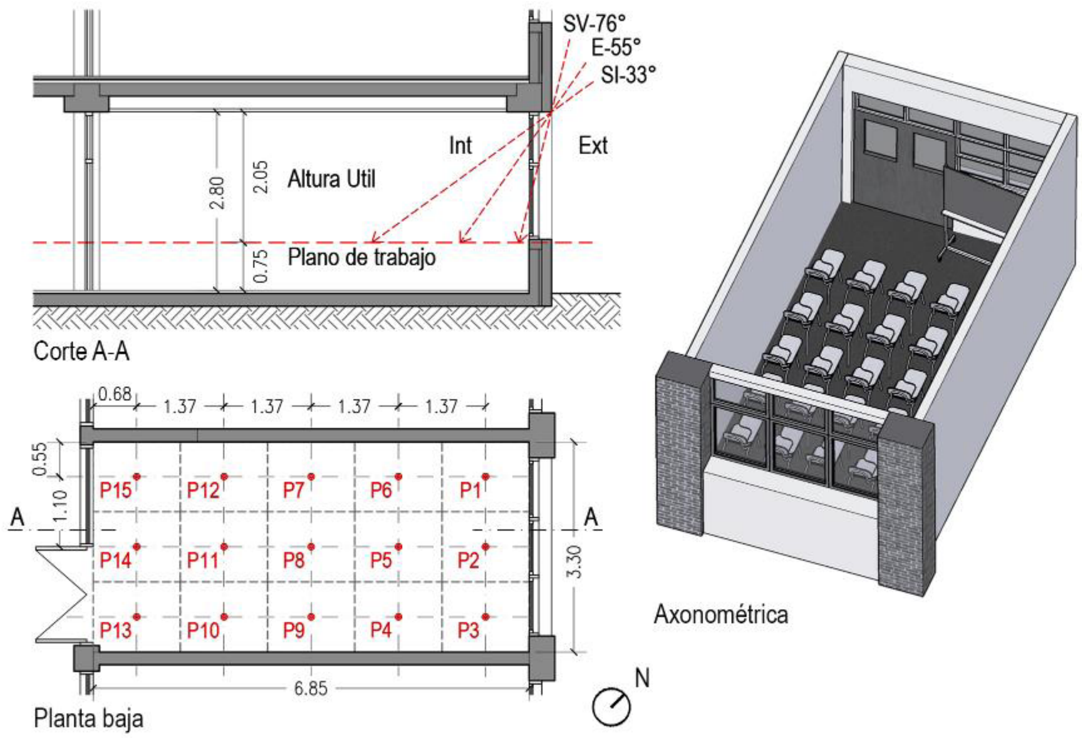

Figure. 4. Plan, cross-cut, and axonometric of the existing classroom with measurement and simulation points. Source: Own preparation.

designed as an administrative office building. The lack of physical space for teaching meant that the ground floor box offices were used as classrooms. The analyzed space is shown in Figures 2 and 3.

The chosen classroom is rectangular, measuring 6.85m x 3.30m. One of the short sides is an outside wall, which has an opening divided into 3 sections, facing north and without exterior protections. The whiteboard area is located next to the door; therefore, the opening is set at the back of the classroom, with its back to the desks. The opening has blackout curtains, which are closed when the classroom is in use (Figure 3).

2- DIAGNOSTIC STAGE.

Stage a

In the first stage, a preliminary exploratory study was made, which pursued two objectives. The first consisted in determining lighting levels of the existing classroom, comparing data obtained through two methods, onsite measurements and simulations, and using two pieces of lighting simulation software: Velux Daylighting Visualizer, developed by the Velux windows company, and Climate Studio, developed by Solemma as a plugin for Rhinoceros 3D, which uses the Radiance calculation engine.

Then, the data obtained were compared to appreciate if they yielded consistent results. It was decided to carry out this study on August 28th, 2019, between 9 am and 1 pm. Both the onsite measurements and the use of simulation software were carried out by architects working in UNVM's Planning area, that is to say, the process involved a previous training stage. Once the consistency of the data obtained was determined, the second objective was to evaluate which strategy (measurement or simulation) and which software (Velux or Climate Studio) best fit the daily work process followed by the Planning architects, to suggest a method to be used in future project processes.

The measurements were made following the procedure described in the "Lighting Measurement in the Work Environment Protocol" (SRT resolution 84/2012). The analyzed classroom was divided into a grid of 5 x 3 areas, resulting in 15 measurement points, one point for each desk, located at a height of 0.75m from the finished floor level (Figure 4). The measurements were made using a previously calibrated luxmeter. Data were collected once per hour, at 10 am (with cloudy sky), at 11 am (with intermediate sky), and at 12 pm and 1 pm (with clear sky). The simulations were configured using the same grid and height of points, to contrast the results with the measured data.

Stage b

Once both pieces of software were tested, it was determined that Climate Studio had a closer fit to the measurements, and its use was user-friendly for Planning architects. Stage 2 then focused on assessing

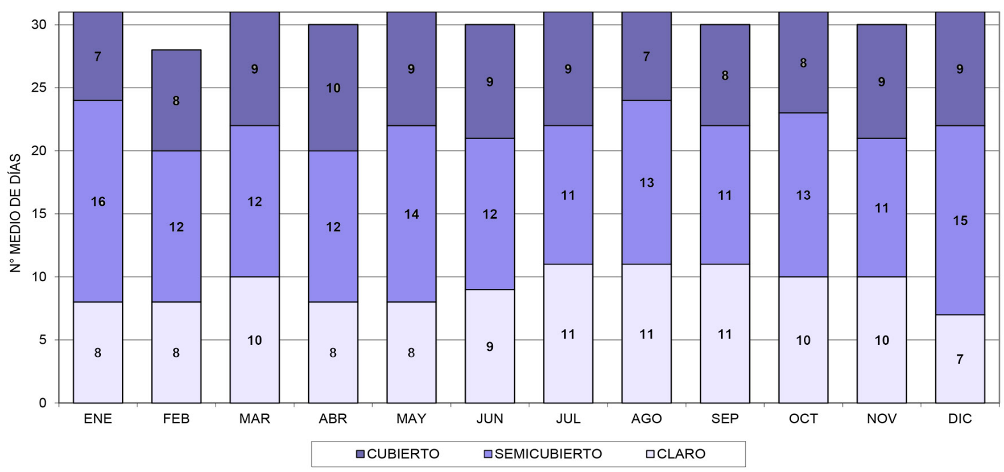

Figure. 5. Percentage of types of sky (overcast, partly cloudy, and clear) throughout the year. Source: Airport Weather Station data included in Gonzalo (2015).

Type of Surface	% Reflex.	Color			Spec.	Roughness
	R	R	G	B		
Walls (White Painted Room)	81.19%	0.830	0.808	0.719	0.36	0.200
Floor (Blue Carpet)	6.44%	0.037	0.07	0.300	0.01	0.300
Ceiling (White Painted Room)	82.20%	0.844	0.817	0.722	0.44	0.200
Equipment (Wood Laminate Table)	50.92%	0.603	0.471	0.304	1.41	0.100
Equipment Structure	47.21%	0.456	0.452	0.428	2.07	0.100
Whiteboard (Green Door Panel)	24.10%	0.211	0.254	0.202	0.17	0.200
Carpentry (White Aluminum)	78.24%	0.745	0.773	0.767	1.72	0.200
Light tray (Whiteboard Paint)	94.42%	0.895	0.897	0.867	4.99	0.010

Table 2. Levels and uniformity of illuminance in the existing classroom. Intermediate sky. Source: Preparation by the authors.

the lighting conditions of the chosen classroom based on the variables and indicators presented in Table 1: illuminance, uniformity of illuminance, and glare (DGP), using just the Climate Studio simulation software.

The simulated values correspond to an intermediate type of sky, predominant in Villa María. Figure 5 shows the monthly percentages of each type of sky during the months of the year (overcast, partly cloudy, and clear). The predominant skies are the partly-cloudy or intermediate ones.

Table 2 illustrates the types of surfaces used in the simulations, with their respective coefficients (Reflection [R], RGB Color Indices, Specularity, and Roughness). The materials presented were used both in the existing and the proposed classroom.

The points grid prepared previously was maintained and it was chosen to assemble a grid that contained simulated data for 3 months of the year and 3 times of the day. The months of March, July, and November were chosen, as these mark the start and end of the class periods. Data were simulated at 9 am, 1 pm, and 5 pm, following the teaching schedule. The results were compared with permissible ranges of mean illumination and uniformity of daylight, found in Addendum VI Decree 351/79 (Law No. 19,587).

The method selected to simulate glare was the Daylight Glare Probability (DGP). To define the evaluation point, the most unfavorable location that an observer could have inside the classroom was considered. In the case of the existing classroom, it was the position of the teacher sitting in front of the whiteboard (1.15 cm from the floor level), since to address the students they must look towards the window.

The range of light comfort parameters considered to analyze the results was: Illuminance between 500 and

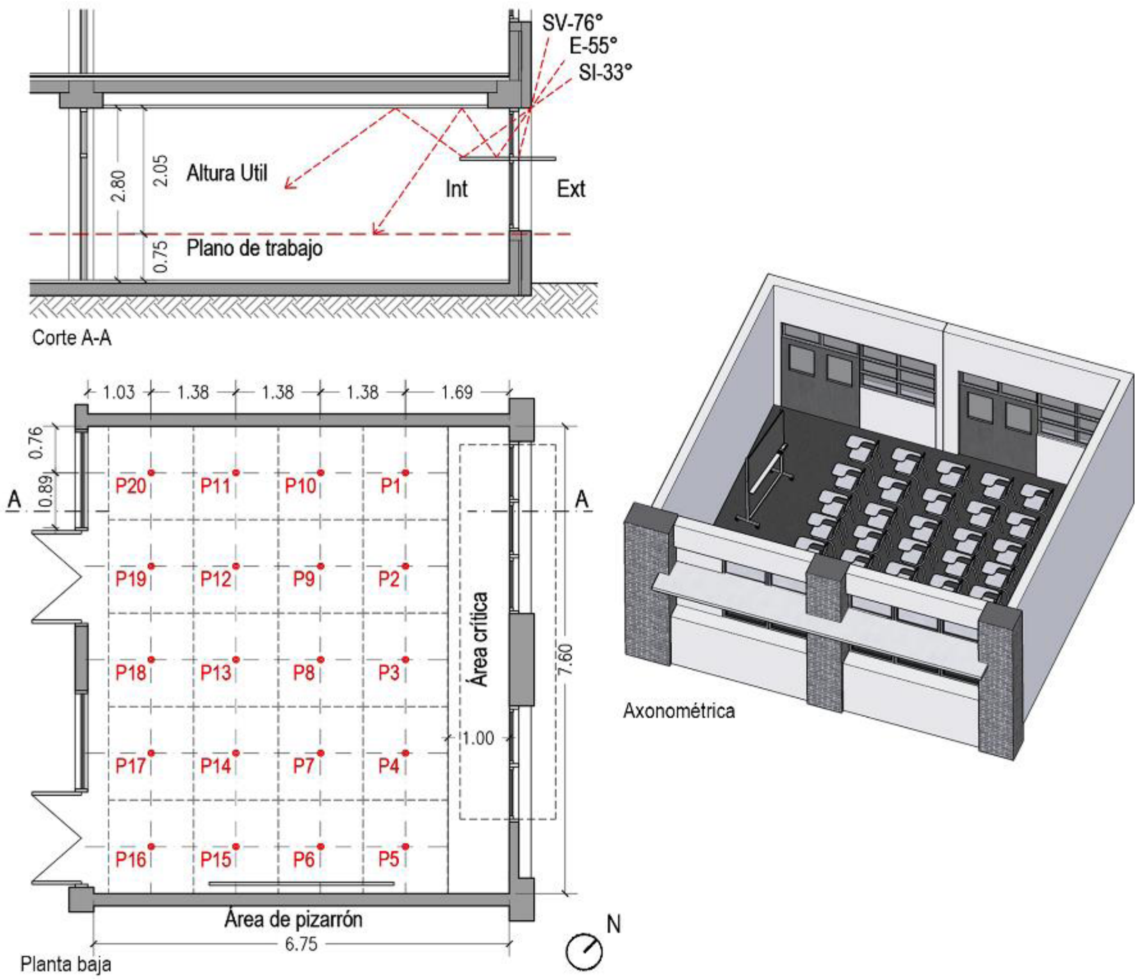

Figure 6. Plan, cross-section, and axonometric of the proposed classroom with measurement and simulation points. Source: Preparation by the authors.

750 lux levels (minimum and recommended levels for classrooms according to DIMEN, 1998, respectively); Uniformity of illuminance > 0.5 (according to the requirement of Decree No. 351/79); and a margin of glare perceptible up to 38% (levels established by Wienold & Christofferen, 2006).

3. PROPOSAL STAGE

This stage involved the elaboration and evaluation of an optimization proposal based on the diagnosis made, using the same indicators as those in the diagnostic stage, to assess the improvements.

It was considered that the building is already built, therefore, the proposed alternative had to feasibly be executed and easy to implement. The proposal is described below and detailed in Figure 6.

1. It was proposed to dismantle the partition wall between classrooms, combining two spaces to form a larger square classroom, with a greater opening to the outside.
2. The whiteboard location was moved to one of the side partitions of the classroom. In addition, it was proposed to protect the whiteboard area from direct solar penetration by replacing one of the glazed panels of the existing opening with a blind panel.
3. Changes were made in the desk layout, leaving a strip of 1.00 m from the outer wall (critical area) to avoid excess light values and visual discomfort on the work planes. With the new arrangement of the whiteboard, the openings are arranged to the left of the desks.
4. A light shelf was placed, dividing the existing opening into two vertical panels, to reflect the incident light towards the surface of the ceiling, thus achieving a greater light penetration and a more uniform distribution.

As in the diagnostic stage, to define the glare assessment point, the most unfavorable location that an observer could have inside the classroom was considered. After changing the whiteboard's location, the most unfavorable position is no longer that of the teacher, but that of a student sitting on the left side of the classroom, facing the whiteboard.

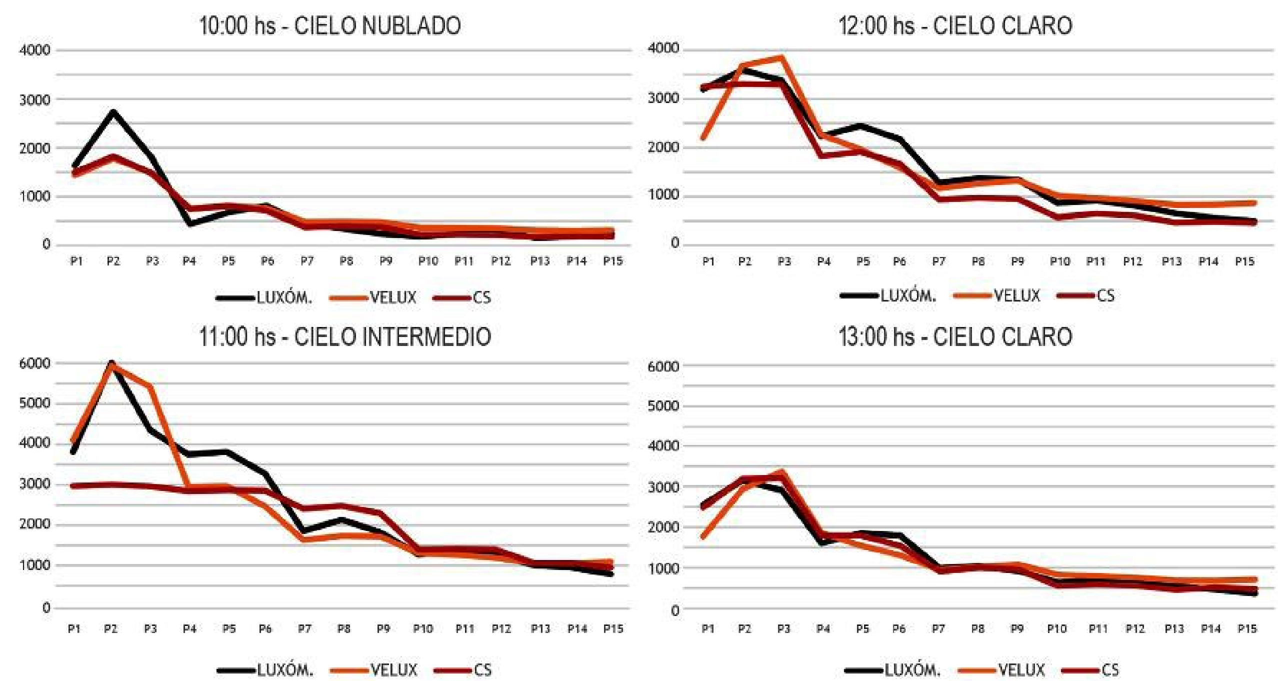

Figure 7 Comparative graphs between measured and simulated results. Source: Preparation by the authors.

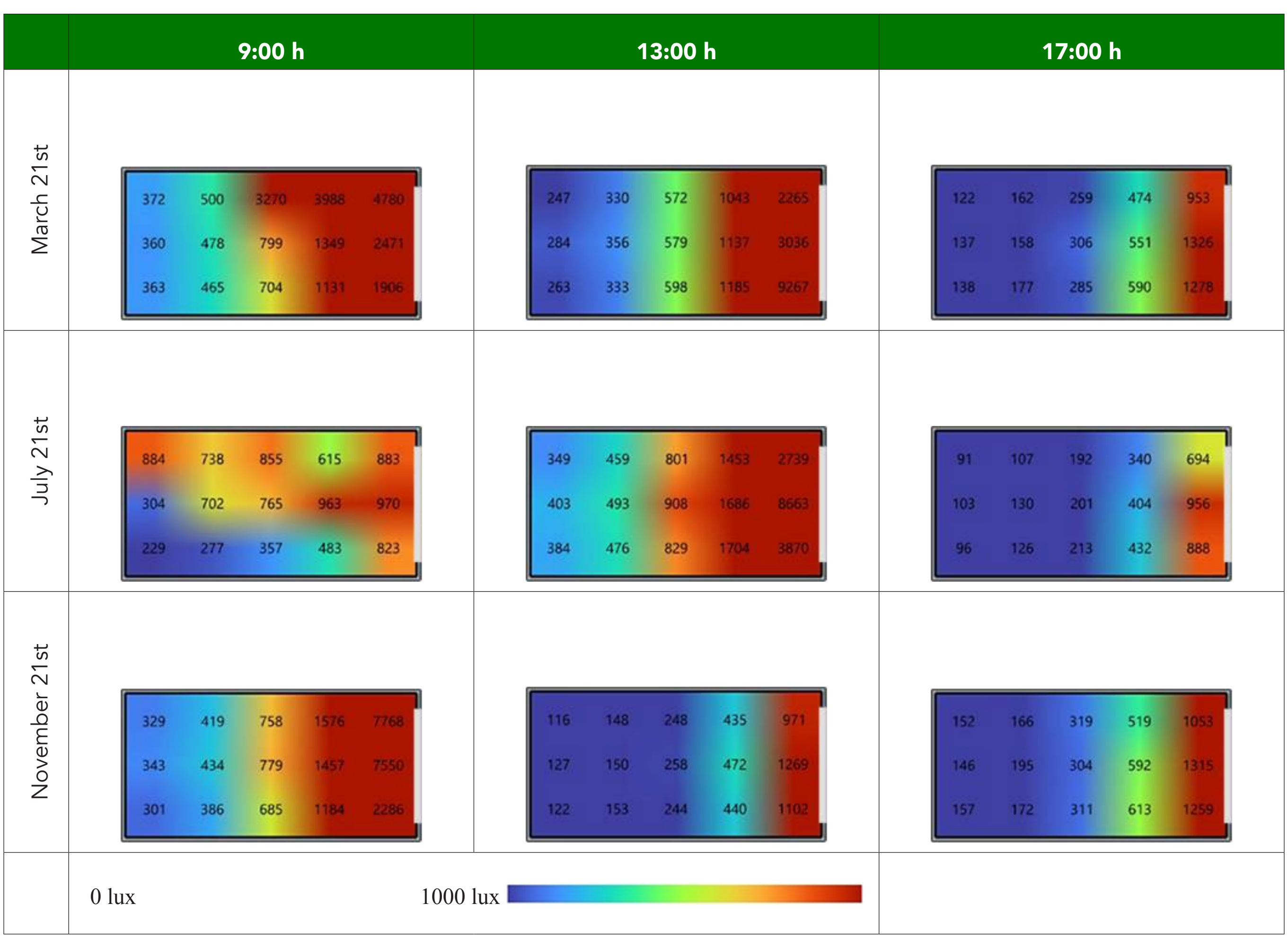

Figure 8. Lighting levels in the existing classroom. Intermediate sky. Source: Preparation by the authors

	March 21st			July 21st			November 21st		
	9:00	13:00	17:00	9:00	13:00	17:00	9:00	13:00	17:00
P-1	4780	2265	953	883	2739	694	7768	971	1053
P-2	2471	3036	1326	970	8663	956	7550	1269	1315
P-3	1906	9267	1278	823	3870	888	2286	1102	1259
P-4	1131	1185	590	483	1704	432	1184	440	613
P-5	1349	1137	551	963	1686	404	1457	472	592
P-6	3988	1043	474	615	1453	340	1576	435	519
P-7	3270	572	259	855	801	192	758	248	319
P-8	799	579	306	765	908	201	779	258	304
P-9	704	598	285	357	829	213	685	244	311
P-10	465	333	177	277	476	126	386	153	172
P-11	478	356	158	702	493	130	434	150	195
P-12	500	330	162	738	459	107	419	148	166
P-13	372	247	122	884	349	91	329	116	152
P-14	360	284	137	304	403	103	343	127	146
P-15	363	263	138	229	384	96	301	122	157
Emáx.	4780	9267	1326	970	8663	956	7768	1269	1315
Emin.	360	247	122	229	349	91	301	116	146
Emed.	1529.1	1433.0	461.1	656.5	1681.1	331.5	1750.3	417.0	484.9
Un	0.24	0.17	0.26	0.35	0.21	0.27	0.17	0.28	0.30

Table 3. Levels and uniformity of illuminance in the existing classroom. Intermediate sky. Source: Preparation by the authors.

RESULTS

DIAGNOSIS OF THE EXISTING CASE

Diagnosis: Stage a

Firstly, the results of lighting levels in the existing classroom, obtained by measurement and simulation, are presented comparatively (Figure 7). It can be seen that the simulated values are true to the values measured with a luxmeter. At 11 am, the intermediate sky condition shows a greater difference between the simulated and the measured results.

It is confirmed that the values obtained by Climate Studio are closer to the measurements than those obtained using Velux DV. This is because Climate Studio has a more accurate calculation engine.

The points closest to the window (P1 to P3) register values of more than 1000 lux in the four times analyzed, exceeding the recommended ranges and reaching, in some cases, points of visual discomfort (>5000 lux). All the points measured and simulated at 11 am have excess light values (> 1000 lux) for the considered range (between 500 and 750 lux). As the points move away from the window, the lighting level decreases. Points P4 to P7 show results close to the visual comfort range at 10 am (400 to 600 lux). However, from 11 am to 1 pm there is excess light (1000 to 2000 lux). The points that are in the middle of the classroom (P7 to P12) reach levels close to visual comfort at 12 pm and 1 pm. At the furthest points, P13 to P15, at 10 am, the illumination decreases to insufficient levels (<200 lux).

Diagnosis: Stage b

Next, the results of the evaluation of the indicators studied during 3 moments of the year are presented. Regarding lighting levels, the grid of Figure 8 and Table 3 shows lighting level results for the 3 months and simulated times.

A relationship with previous results is seen here: very high levels of Emax at points near openings, close to 9200 lux in the early hours of the morning (due to

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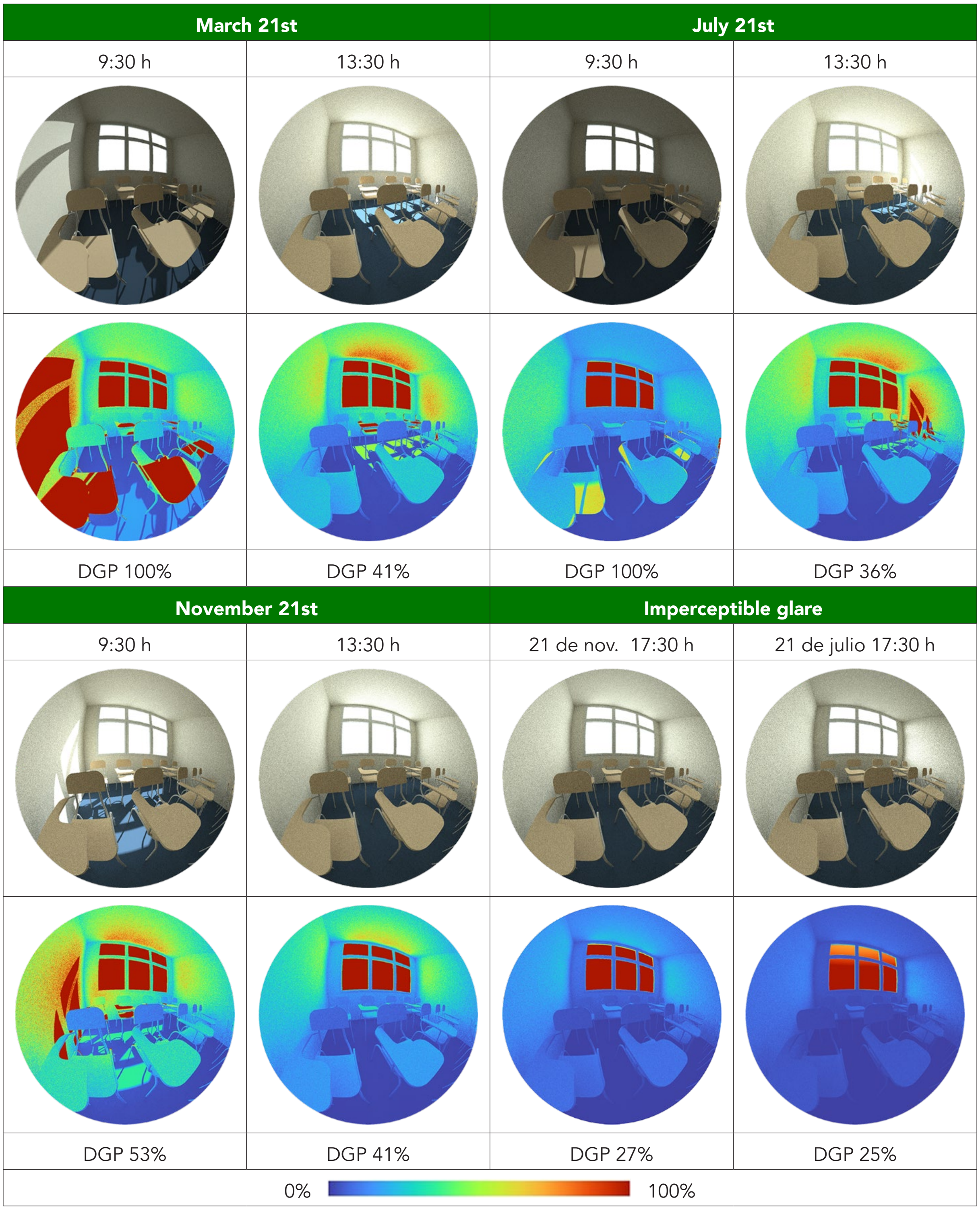

Figure 9. DPG glare values (%) of the existing classroom. Source: Preparation by the authors

direct solar penetration), which decrease during the day until reaching 1300 lux at 5 pm. The Emin values corresponding to the other end of the classroom show a significant reduction in illuminance, reaching levels of less than 300 lux at the same time.

As for uniformity in the daylight distribution, the values are, in all cases, below 0.5, i.e., none of them meet the established requirements. Only one of the cases (July at 9 am) has an acceptable uniformity. In general, the light uniformity is poor, as there are very bright spots and very poorly lit spots.

GLARE

Figure 9 expresses the results of the DGP index (%). It can be noted from this that the results are consistent with the previous illuminance values. The probability

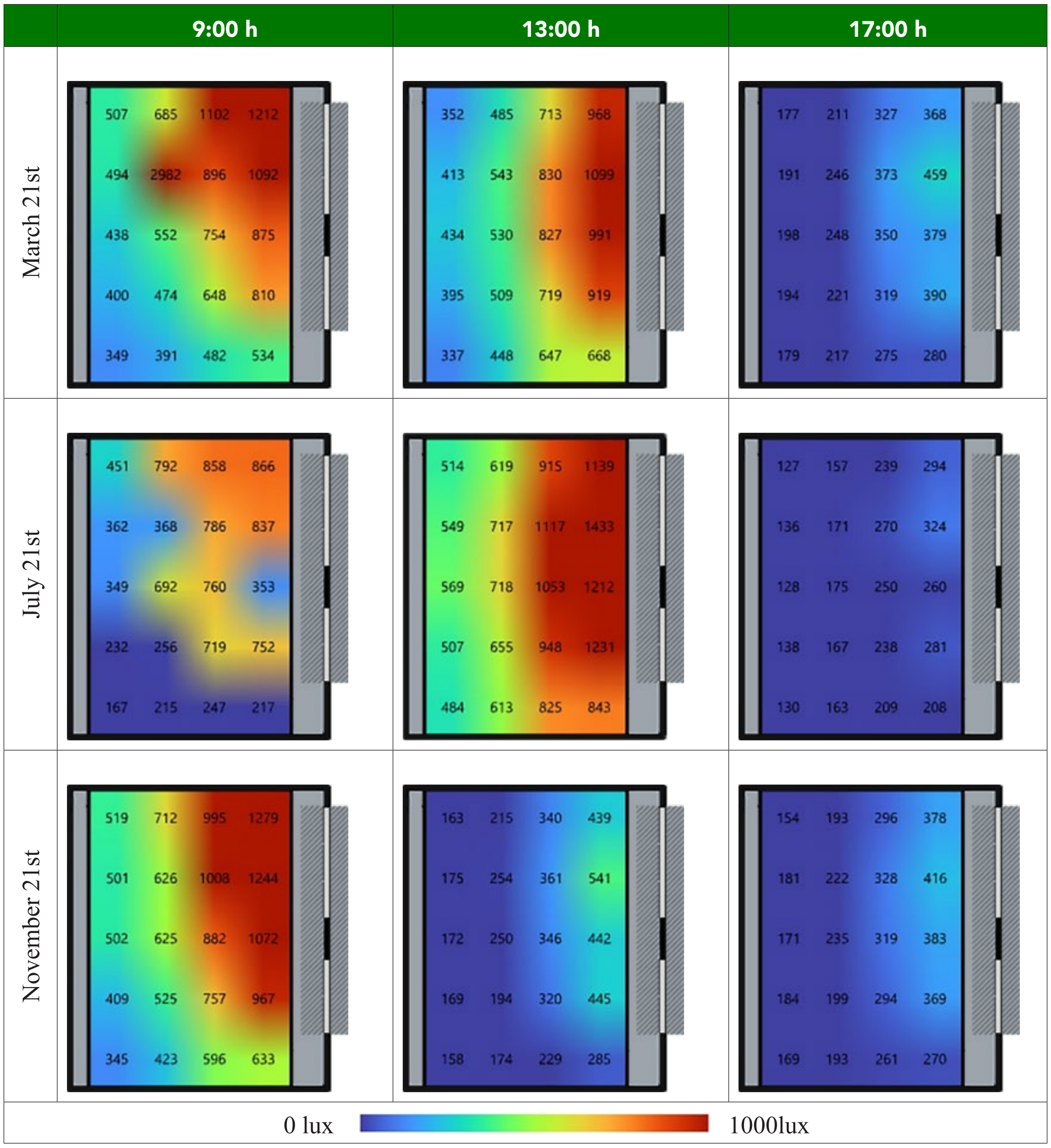

Figure 10. Lighting levels in the proposed classroom. Intermediate sky. Source: Preparation by the authors

of glare is highest during the morning in all cases, reaching peaks of 100% (intolerable) on March 21st and July 21st at 9:30 am, at times of direct solar penetration. This situation also coincides with the higher illuminance values and the low light distribution levels.

From 1:30 pm, the values begin to decrease. On July 21st, glare is noticeable according to the established ranges (36%). However, both March 21st and November 21st continue to present bothersome values (41%). At 5:30 pm, in all cases, the occurrence of glare is imperceptible, registering values of 29% (March 21st), 25% (July 21st), and 27% (November 21st).

PROPOSED CASE

LIGHTING LEVELS

The grids of Figure 10 and Table 4 show the lighting level results of the proposed classroom. On one hand, a considerable reduction in Emax can be observed, with values between 500 and 1000 lux, close to the openings, presenting a peak of 2962 lux on March 21st at 9 am. This happens because the light tray obstructs direct solar penetration.

The points in the sectors furthest from the openings have values between 350 and 510 lux during the morning in

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	March 21st			July 21st			November 21st		
	9:00	13:00	17:00	9:00	13:00	17:00	9:00	13:00	17:00
P-1	1212	968	368	866	1139	294	1279	439	378
P-2	1092	1099	459	837	1433	324	1244	541	416
P-3	875	991	379	353	1212	260	1072	442	383
P-4	810	919	390	752	1231	281	967	445	369
P-5	534	668	280	217	843	208	633	285	270
P-6	482	647	275	247	825	209	596	229	261
P-7	648	719	319	719	948	238	757	320	294
P-8	754	827	350	760	1053	250	882	346	319
P-9	896	830	373	786	1117	270	1008	361	328
P-10	1102	713	327	858	915	239	995	340	296
P-11	685	485	211	792	619	157	712	215	193
P-12	2962	543	246	368	717	171	626	254	222
P-13	552	530	248	692	718	175	625	250	235
P-14	474	509	221	256	655	167	525	194	199
P-15	391	448	217	215	613	163	423	174	193
P-16	349	337	179	167	484	130	345	158	169
P-17	400	395	194	232	507	138	409	169	184
P-18	438	434	198	349	569	128	502	172	171
P-19	494	413	191	362	549	136	501	175	181
P-20	507	352	177	451	514	127	519	163	154
Emáx.	2962	1099	459	866	1433	324	1279	541	416
Emin.	349	337	177	167	484	127	345	158	154
Emed.	782.9	641.4	280.1	514.0	833.1	203.3	731.0	283.6	260.8
U	0.45	0.53	0.63	0.32	0.58	0.62	0.47	0.56	0.59

Table 4. Levels and uniformity of lighting in the proposed classroom. Intermediate sky. Source: Preparation by the authors.

March and July, reaching levels of visual comfort. It will be necessary to reinforce with artificial lighting in November at 1 pm and in the 3 months at 5 pm because the values are low (< 300 lux).

The uniformity in the daylight distribution registers an increase in all values, except in July (9 am), which shows a minimum decrease (from 0.35 to 0.32). The lowest uniformity values occur at 9 am (0.45 in March, 0.32 in July, and 0.47 in November), and are very close to the requirements established in Argentina (0.5). Even so, they are considered acceptable in the presented range. As of 1 pm, the uniformity registers results above 0.5 in all cases.

GLARE

The glare results of the proposed classroom are shown in Figure 11.

The results obtained are consistent with the reduction of illuminance values and the increase of uniformity in the daylight distribution. The glare probability also shows a significant reduction during the morning in all cases. Despite this, the values still correspond to the bothersome glare range with 44% (March 21st), 39% (July 21st), and 35% (November 21st). From 1:30 pm, the values are located in the range of perceptible (31% in March and July) and imperceptible (29% in November and all cases at 5:30 pm) glare.

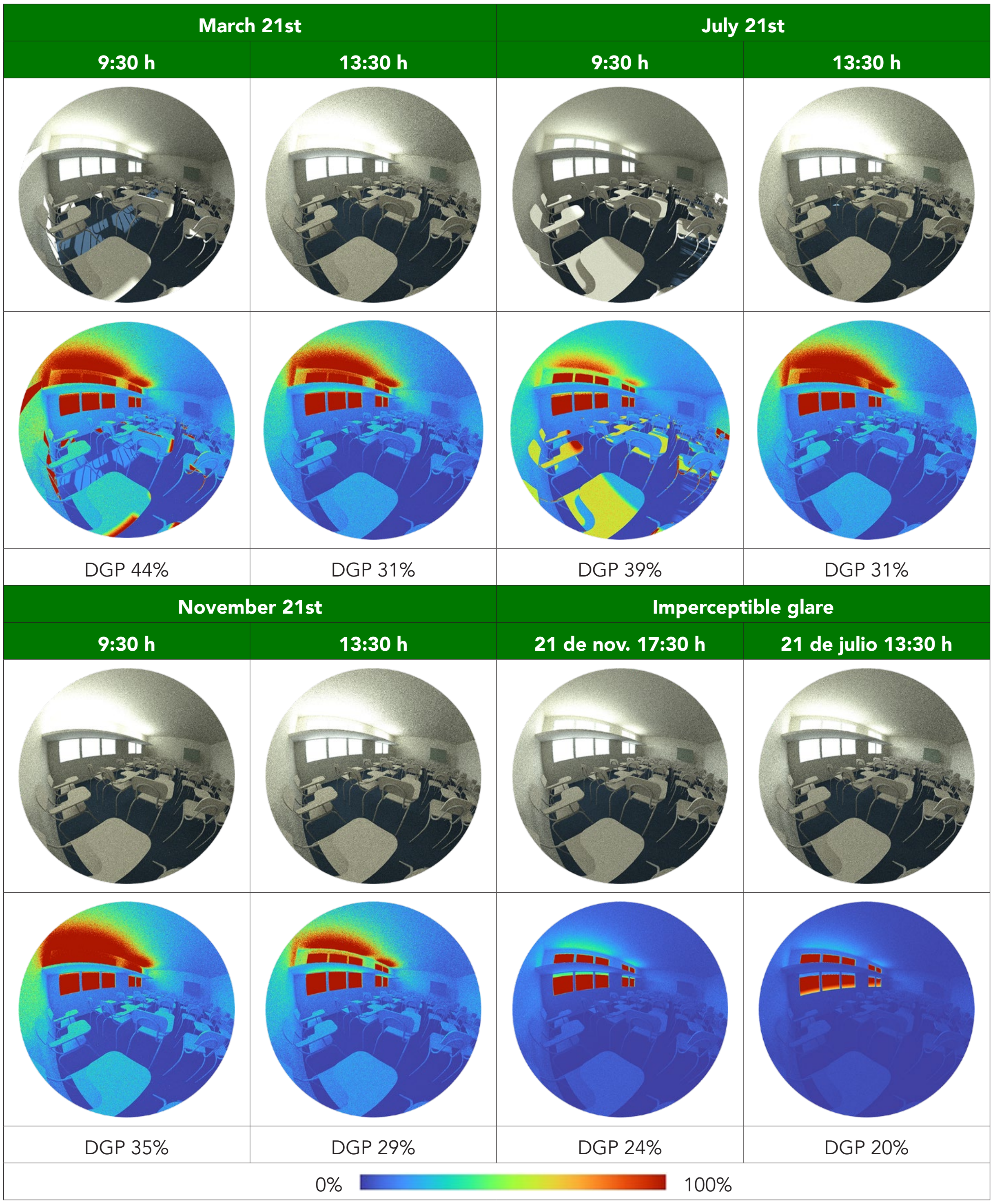

Figure 11. DPG glare values (%) of the proposed classroom. Source: Preparation by the authors.

DISCUSSION

The functional layout of the existing classroom is inefficient. The points with the highest level of illumination are found at the back of the classroom, next to the window, and not in the focal point of the students' attention (whiteboard area). Therefore, at times when artificial lights are not on, the students cast a shadow on the work plane of the desk. Likewise, the direct solar penetration there is during the morning causes the desks next to the window to have excess light on the work plane, reaching values of visual discomfort. The results also showed that there are serious problems of glare that a person looking at the window would have, namely, compromising the work performance of the teacher who looks at the desks from the whiteboard area.

The proposed alternative involved significant improvements in the classroom. The proposed desk layout prevents students from casting shade on the work plane, and the teacher from looking towards the windows when teaching. The incorporation of a light tray made it possible to block direct solar radiation, preventing its incidence on the work planes, which significantly improves illuminance values near the window. In addition, the reflective surface of the tray allowed reflecting incident light into the classroom, allowing a more uniform distribution of lighting inside the classroom. Although significant reductions were achieved, there is still room for improvement. The lighting uniformity values are still low (<0.50) and the glare values express the perception of some discomfort during the morning (44% and 39%). Table 5 summarizes the results obtained and comparatively presents them, to show the improvements achieved.

CONCLUSIONS

This work aimed at identifying passive design strategies to achieve recommended levels of indoor light comfort in educational buildings. The results obtained show the achievement of the goals set out. Added to this, the results have the benefit of potential electricity saving from using daylighting, which can be quantified in subsequent studies.

The discussion of the results indicates that they can continue to be optimized, especially during morning hours. In future studies, it may be proposed to incorporate interior roller-type curtains with sunscreen fabrics, which act as diffusing screens, to achieve a more uniform illuminance and avoid bothersome glare. In the same way, the results obtained can be considered in the design, to integrate daylighting with artificial lighting, in the choice of suitable types of lights.

Both the performance of the existing classroom, the design of alternatives, and the preview of results were possible thanks to the use of measurement and simulation tools and procedures, which allowed training professional architects from SPTSyM - UNVM in the management of daylighting-associated indicators and their inclusion within design practices. The Climate Studio software was chosen over the Velux Daylight Visualizer Software, given its easy operation, its better graphical interface, its extensive library of materials, and a better fit of its results to the measurement values. These tools and work procedures will be taken into account in the development of future projects.

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	Indic.	March 21st			July 21st			November 21st		
		09:00	13:00	17:00	09:00	13:00	17:00	09:00	13:00	17:00
AE	E max	4780	9267	1326	970	8663	956	7768	1296	1315
	E min	360	247	122	229	349	91	301	116	146
	E med	1529.1	1433.0	461.1	656.5	1681.1	331.5	1750.3	417.0	484.9
AP	E max	2962	1099	459	866	1433	324	1279	541	416
	E min	349	337	177	167	484	127	345	158	154
	E med	782.9	641.4	280.1	514.0	822.1	203.3	731.0	283.6	260.0
AE	U	0.24	0.17	0.26	0.35	0.21	0.27	0.17	0.28	0.30
AP	U	0.45	0.53	0.63	0.32	0.59	0.62	0.47	0.56	0.59
AE	DGP	100%	41%	29%	100%	36%	25%	53%	41%	27%
AP	DGP	44%	31%	23%	39%	31%	20%	35%	29%	24%

Table 5. Comparative analysis between the existing and proposed classroom. Source: Preparation by the authors.

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USE OF LIGHTWEIGHT MATERIALS FOR THE PRODUCTION OF LOW-DENSITY CONCRETE: A LITERARY REVIEW[1]

USO DE MATERIALES LIGEROS PARA LA PRODUCCIÓN DE HORMIGÓN DE BAJA DENSIDAD: UNA REVISIÓN LITERARIA

Liseth Díaz-Merino
Bachiller de en Ingeniería Civil, Estudiante de Ingeniería Civil, Universidad Señor de Sipán. Chiclayo, Perú
https://orcid.org/0000-0002-7339-9898
dmerinoliseth@crece.uss.edu.pe

Luis Fernando Altamirano-Tocto
Bachiller de en Ingeniería Civil, Estudiante de Ingeniería Civil, Universidad Señor de Sipán, Chiclayo, Perú
https://orcid.org/0000-0002-9126-8787
atoctoluisferna@crece.uss.edu.pe

Sócrates Pedro Muñoz-Pérez
Doctor en Gestión Pública y Gobernabilidad, Director de la Escuela de Ingeniería Civil, Profesor- Investigador, Universidad Señor de Sipán, Chiclayo, Perú
https://orcid.org/0000-0003-3182-8735
msocrates@crece.uss.edu.pe

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RESUMEN

A lo largo del siglo XX la industria de la construcción viene empleando grandes cantidades de hormigón, en consecuencia, ha aumentado la demanda de los agregados naturales, de manera que se hace necesario contrarrestar el uso de estos. Frente a tal contexto, el presente trabajo tiene como objetivo presentar una revisión literaria del uso de materiales ligeros para producir hormigón de baja densidad, el cual posee aislamiento térmico que se produce principalmente con agregados ligeros. En ese marco, se revisaron 52 artículos indexados entre los años 2017 y 2021 en la base de datos de Scopus. Los resultados revelaron que, empleando ceramsite de lodo como árido, se puede obtener una densidad de 1251 kg/m^3 y, con agregados de arcilla expandida, se puede obtener resistencias a la compresión desde 17.7 a 66.1 MPa. En conclusión, se logró determinar que con el uso de materiales livianos en la producción de hormigón se puede disminuir su densidad, además de contribuir en la reducción de daños que se generan al medio ambiente.

Palabras clave:
agregados ligeros, aislamiento térmico, hormigón de baja densidad, residuos.

ABSTRACT

Throughout the 20th century, the construction industry has been using large quantities of concrete. Consequently, the demand for natural aggregates has increased, making it necessary to counteract their use. In this context, this work aims at presenting a literature review of the use of lightweight materials to produce low-density concrete, whose thermal insulation is mainly made using lightweight aggregates. In this framework, 52 articles indexed between 2017 and 2021 in the Scopus database were reviewed. The results revealed that, by employing ceramsite sludge as an aggregate, a density of 1,251 kg/m3 can be obtained and, with expanded clay aggregates, compressive strengths from 17.7 to 66.1 MPa can be obtained. In conclusion, it was determined that the use of lightweight materials in concrete production can reduce its density, in addition to contributing to the reduction of environmental damage.

Keywords:
lightweight aggregates, thermal insulation, low-density concrete, waste.

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INTRODUCTION

Concrete is the most widely used material in the construction industry. In 2015 alone, 20 billion tons were used worldwide. This material comprises conventional aggregates that correspond to between 55% and 88% of the total volume, and it is estimated that by 2023, its production will increase to 48.3 billion tones, which may lead to overexploiting the aggregate quarries (Pokorny, Ševcík, Šál & Zárybnická, 2021). Concrete is typically used in the construction of structures such as buildings, bridges, and water conservation projects (Ojha, Singh & Behera, 2021). Said structures, once they have fulfilled their life cycle, are destroyed and thrown away, generating great damage to the environment (X. Sun *et al.,* 2021).

Energy consumption has attracted considerable attention from Governments, industries, and the scientific community. From the starting point of a lack of available energy resources, different research projects have been made on efficient materials (Jones, Ozlutas & Zheng, 2017). In this context, many efforts have been made to study new engineering materials that can absorb energy, such as lightweight concrete, which represents a significant step toward reducing the amount of greenhouse gas emissions (Palanisamy *et al.,* 2020.

It is for this reason that countries with better economic positions and technology related to research have been implementing the use of light aggregates in concrete, seeking a construction material that looks to take care of the planet (Aley Kumar, Karthik & Mangala Keshava, 2020). This type of technology reduces environmentally harmful impacts, on being industrial or natural products that can be reused and replace conventional aggregates, as they perform similar roles to those in concrete (Kailash & Rashmi, 2018), and likewise generate alternative solutions for the lack of natural resources (X. Sun *et al.* 2021). In this way, it is possible to recycle waste materials, obtaining lightweight aggregates to thus manufacture environmentally friendly concrete (Hamidian & Shafgh, 2021).

Lightweight concrete, also known as "special low-density concrete", which has advanced thermal insulation, is mainly produced with lightweight aggregates or a cellular matrix (Y. Sun *et al.,* 2021). These comprise around 50% of the volume of concrete, while the material made from a cellular matrix is generally known as "foam concrete", due to the pores introduced by a foaming agent (Chung, Sikora, Stephan & Abd Elrahman, 2020).

Concrete with lightweight aggregates can be obtained naturally or by processing environmental and industrial waste. Thanks to the different useful properties of lightweight concrete as a construction material, it is becoming more widely known (Pateriya, Dharavath & Robert, 2021). Given its low density, it reduces the dead loads in constructions (Al-lami & Al-saadi, 2021), so this concrete can produce structural elements with a lower weight, which is why they improve the load capacity which, at the same time, enables them to be used in construction elements like load-bearing walls, as they are also an effective thermal insulation material (Appavuravther, Vandoren & Henriques, 2021). In this sense, the use of structural lightweight concrete leads to a lighter structure that offsets any lateral force provoked by an earthquake (Yinh *et al.*, 2021).

Ultimately, the main goal of using lightweight concrete is to simplify the design of structural elements to create sustainable infrastructures. Its application in construction reduces costs, facilitates the construction process, and has the advantage of being a relatively "green" construction material (A. Mohamed, E. Mohamed, Sang-Yeop, Pawel & Dietmar, 2019). Nowadays, there are different types of lightweight concrete, depending on the lightweight aggregate used, such as expanded clay, plastic, wood, tiles, as well as natural porous materials, like pumice, which are normally used as an aggregate in lightweight concrete mixes (Strzałkowski, Sikora, Chung & Elrahman, 2021). In the same vein, their traditional application in the construction industry is considered, for example, in masonry walls, as well as in different structural elements, such as lightened slabs and columns (Hücker & Schlaich, 2017).

Specifically, the purpose of this article is to present the literature review made on the use of lightweight materials that are capable of producing low-density concrete.

METHODOLOGY

This article falls within an exploratory experimental process, whose purpose is to analyze different articles from specialist journals on studies related to low-density concrete and lightweight materials, used in construction sites. In this way, a search was made on the Scopus database between 2017 and 2021, using the keywords in English, "lightweight materials in low-density concrete", and incorporating the Boolean operators "and", "or", "and not". With the operator "and", 154 articles were found, before then filtering by the areas of "Engineering", "Material Science", and document type, "article". This process resulted in 34 articles, out of which 7 were chosen. This was repeated with the operator "or", finding 33,368 documents. This was then filtered by area and document type, obtaining 7,456, from which

Database	Year of Publication					
	2017	2018	2019	2020	2021	Total
Scopus	3	1	4	13	31	52
Total	3	1	4	13	31	52

Table 1. Distribution of articles references by year of publication and database. Source: Prepared by the authors.

Database	Keywords with Boolean operators	Documents Found	Search Years	Search Filters	Documents found using filters	Documents chosen
Scopus	(Lightweight AND materials) AND (low-density AND concrete)	158	2017-2021	Area: "Engineering" "Material Science" Document type: Article	34	7
	(Lightweight AND materials) OR (low-density AND concrete)	33368	2017-2021	Area: "Engineering", "Material Science" Document type: Article	7456	32
	(low-density AND concrete) AND NOT (lightweight AND materials)	678	2017-2021	Area: "Engineering" "Material Science" Document type: Article	138	13

Table 2. Summary, criteria, and search results from the Scopus database. Source: Prepared by the authors

32 articles were chosen. Finally, with the operator "and not", 678 documents were found. These were then filtered once more by area and document type, ending with 138, of which 13 articles were chosen. This methodology is presented in greater detail in Table 1, Table 2, and Figure 1.

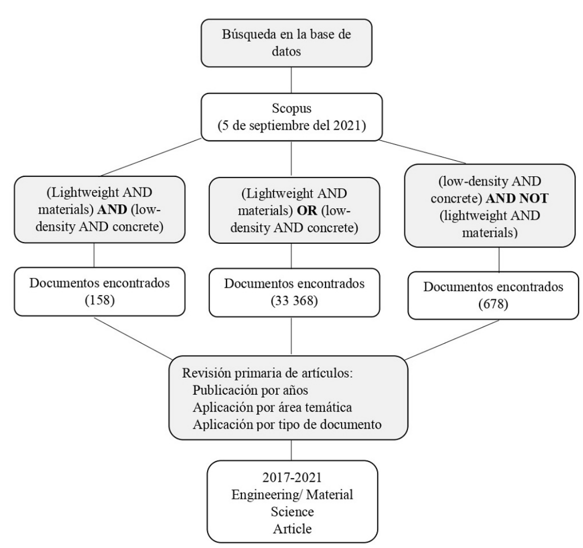

Figure 1. Article search in Scopus database. Source: Prepared by the authors.

RESULTS AND DISCUSSION

LIGHTWEIGHT MATERIALS

Lightweight aggregates are beneficial because they reduce the dead loads of a structure and provide internal curing to mitigate early cracking, while also reducing the effects of an earthquake (Muralitharan & Ramasamy, 2017). However, the dose of the mix and the handling of recently mixed lightweight aggregate concrete (LWAC) are not as simple as those of conventional concrete (J. Kim, Lee & Y. Kim, 2021).

The construction industry has a great impact on economic growth, but, at the same time, is known as one of the main consumers of natural resources and energy for the manufacture of raw materials around the world (Chung, Sikora, Kim, El Madawy & Abd Elrahman, 2021). Hence, the concentration in the implementation of waste and byproducts to substitute natural and manufactured materials is ever more important to support the concept of a green product (Moutassem, 2020).

Different types of materials have been used to produce lightweight concrete, such as lightweight

Type of concrete	Standard (ASTM)	Aggregate		Concrete		
		Sizes	Density (Kg/m3)	Types	Density (Kg/m3)	Compressive resistance (MPa)
Structural Concrete	C330	*Fine *Coarse *Combination of fine and coarse Aggregate	* >1120 * >880 * >1040	*Furnace slag *Pulverized ash *Expanded clay *Expanded slate *Pumice *Slag *Limestone *Diatomaceous	1360-1920	17-28

Table 3. Summary of the different sizes of aggregates and types of concrete adding lightweight materials. Source: Maghfouri et al. (2021).

Type of Aggregate	Type of Cement	Aggregate Percentage	Compressive Resistance (MPa	Density (Kg/m3)	Water/ Cement Ratio	Reference
Plastic Lightweight A.	Ordinary Portland	75%	18	1900	0.5	(Alqahtani et al., 2021)
Expanded Polystyrene A.	Ordinary Portland	60%	30.53	1716	---	(Wibowo et al., 2021)
Expanded Polystyrene A.	CEM I 52.5N	15%	32	1900	0.39	(Rosca, 2021)

Table 4. Compressive resistance of artificial lightweight aggregates. Source: Prepared by the authors

aggregates. The exhaustive research of Maghfouri *et al*. (2021) focused on these different types of materials that can be used in LWAC with an apparently outstanding density.

There is a lot of research on materials that can be added to concrete for it to have a lower density (Zade, Bhosale, Dhir, Sarkar & Davis, 2021). For this reason, a systematic review of several studies on material behavior is presented below (Alqahtani & Zafar, 2020), for natural materials, artificial materials, or waste products used in lightweight aggregate concrete (Zeng, Sun, Tang & Zhou, 2020).

ARTIFICIAL LIGHTWEIGHT AGGREGATES

Plastic aggregate

The findings of Dielemans, Briels, Jaugstetter, Henke, and Dörfler (2021) indicated that the use of lightweight plastic aggregates in concrete structures leads to savings of up to 7.23% and 7.18% in the amount of concrete and steel. They also revealed that slab structures with vanes of between 4 and 5 m are the most benefitted from the use of this type of material.

Meanwhile, the analysis of Alqahtani, Abotaleb, and ElMenshawy (2021) states that, by replacing 75% of the volume of natural aggregates with recycled plastic and using ordinary Portland cement with a water-cement ratio of 0.5, the concrete reaches a compressive resistance (*f'c*) of 18 MPa and a density of 1900 kg/m^3.

Expanded polystyrene aggregate

The binding agent used in the research of Wibowo, Lianasari, Wiransya, and Kurniawan (2021) was ordinary Portland cement, with a 60% expanded polystyrene aggregate as a partial replacement of the fine aggregate in the volume. Here, an *f'c* of 30.53 MPa and a density of 1716 kg/m^3 were reached.

Another study made by Rosca (2021) revealed that with the use of CEM I 52.5N cement, this had a

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Type of Aggregate	Type of Cement	Aggregate Percentage	Compressive Resistance (MPa	Density (Kg/m3)	Water/ Cement Ratio	Reference
Diatomaceous Earth A.	Ordinary Portland	40%	13.45	1290	0.55	(Hasan et al., 2021)
Palm Oil Clinker A	CEM I 42.5N	85%	35.56	1933	0.50	(Sarayreh et al., 2020)
Palm Almond and Whelk Shells A	Portland Ordinario	20% c/u	15	1900	0.60	(Ogundipe et al., 2021)

Table 5. Compressive resistance of natural aggregates. Source: Prepared by the authors

w/c ratio of 0.39 and a replacement of 15% of the thick aggregate volume for expanded polystyrene aggregate. It obtained an *f'c* of 32 MPa and a density of 1900 kg/m^3.

The information mentioned in the preceding paragraphs is summarized in Table 4, where it is possible to compare the results of the research of the aforementioned authors.

NATURAL LIGHTWEIGHT AGGREGATES

Diatomaceous earth aggregate

According to the study made by Vinod, Sanjay, Siengchin, and Fischer (2021), diatomaceous earth has a low density, which means that the material is useful to produce lightweight aggregates, specifically in the production of lightweight concrete.

In the work carried out by Hasan, Saidi, and Afifuddin (2021), seven different mixtures were made, from which it was observed that one in particular, had better results: a density of 1290 kg/m^3 and an *f'c* of 13.45 MPa, for a w/c ratio of 0.55, replacing 40% of the natural aggregates in weight.

Palm oil clinker aggregate

The lightweight concrete produced using a mix of waste materials has the advantage of protecting the environment and reducing costs in the construction industry.

In the research made by Sarayreh, Othman, Abdullah, and Sulaiman (2020), it was determined that with the substitution of 85% of coarse aggregate with palm oil clinker aggregate, and with the use of ordinary Portland cement CEM I 42.4 in a w/c ratio of 0.5, an *f'c* of 35.56 MPa is obtained at 28 days, and a density of 1933 kg/m^3.

On the other hand, Ogundipe, Ogunbayo, Olofinnade, Amusan, and Aigbavboa (2021) used 20% palm almond and 20 % whelk shells as a coarse aggregate and 60% natural coarse aggregate. Its w/c ratio was 0.60 and the cement used was ordinary Portland. The experimental results showed that its *f'c* was 15.3 MPa, and its density was 2040 kg/m^3.

Table 5 presents the results mentioned by the authors cited in this section

Expanded clay aggregate

Sindhuja and Bhuvaneshwari (2021) determined that using ordinary Portland cement, with a w/c ratio of 0.45, and with the substitution of 30% of the natural coarse aggregate for expanded clay aggregate to be used in columns with a maximum aggregate size of 15 mm, the lightweight concrete density is 1990 kg/m^{3,} and the *f'c*, at 28 days is 28.3 MPa.

Meanwhile, the article by Rahul and Santhanama (2020) examined concrete samples prepared with expanded clay lightweight aggregate whose maximum size was 10 mm. The binding agent used in the study was Portland cement, in mixtures of up to 30% substitution of coarse aggregate, which managed to reach an *f'c* of 25 MPa, with a w/c ratio of 0.40 and density of 2158 kg/m^3.

Similarly, Long (2020) used Portland cement type I and a w/c ratio of 0.40, obtaining an *f'c* of 19.7 MPa at 28 days, and a density of 1489 kg/m^3, on replacing 40% of the coarse aggregate in volume with expanded clay, whose aggregate size was 7 mm.

Meanwhile, Pontes, Bogas, Real, and Silva (2021) used Portland cement type I 42.5 R, with 15% expanded clay to replace the coarse aggregate, and a w/c ratio of 0.35, obtaining an *f'c* of 66.1 MPa and a density of 1920 kg/m^3.

Bicer (2021) applied expanded clay instead of conventional aggregates to produce low-density construction material. The samples were dried over 28 days at room temperature, and then the

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Type of Aggregate	Type of Cement	Aggregate Percentage	Compressive resistance (MPa)	Density (Kg/m3)	Water/ Cement Ratio	Reference
Expanded Clay A.	Ordinary Portland	30%	28.3	1990	0.45	(Sindhuja y Bhuvaneshwari, 2021)
	Ordinary Portland	30%	25	2158	0.4	(Rahul y Santhanam, 2020)
	Portland Type I	40%	19.7	1489	0.4	(Long, 2020)
	Portland Type I	15%	66.1	1920	0.35	(Pontes et al., 2021)
	Portland Type I 42.5 R	10%	24.68	1420	0.5	(Bicer, 2021)
	CEM I 52.5	40%	17.7	1660	0.45	(Moreno-Maroto et al., 2019)

Table 6: Compressive resistance of expanded clay aggregates. Source: Prepared by the authors.

Type of Aggregate	Type of Cement	Aggregate Percentage	Compressive resistance (MPa)	Density (Kg/m3)	Water/ Cement Ratio	Reference
Pumice	Ordinary Portland	10%	27.1	---	0.45	(Ramanjaneyulu *et al.*, 2019)
	CEM IV 32,5 R	20%	24	1650	0.5	(Bicer y Celik, 2020)

Table 7. Compressive resistance of pumice aggregate. Source: Prepared by the authors.

measurements were made. To prepare the samples, Portland cement type I 42R was used, substituting 10% of the natural aggregates with expanded clay, at a w/c ratio of 0.5. As a result, the *f'c* was 24.68 MPa, the density was 1420 kg/m^3, and its conductivity coefficient was 0.215W/mK. All the samples had a water absorption rate below 30%.

Meanwhile, Moreno-Maroto, Beaucour, González-Corrochano, and Alonso-Azcárate (2019) replaced 40% of the coarse aggregate with expanded clay, using a size of 10 mm and Portland cement CEM I 52.5, for a w/c ratio of 0.45, obtaining an *f'c* of 17.7 MPa and a density of 1660 kg/m^3.

Below, Table 6 provides a summary of the results mentioned by the authors cited in this section.

Pumice aggregate

In their research, Ramanjaneyulu, Seshagiri Rao, and Desai, (2019) replaced coarse aggregate with pumice, whose optimal percentage was 10% of the normal weight aggregate in volume fractions, with a maximum size of 12 mm. In addition, ordinary Portland cement was used in a w/c ratio of 0.45, obtaining an *f'c* of 27.1 MPa, and a flexion resistance of 5.06 MPa.

On the other hand, the optimal pumice proportion used by Bicer and Celik (2020) in their study was 20% of the total volume, in replacement of the natural coarse aggregate. Pozzolanic cement, CEM IV / B (P) 32.5R was used, its w/c ratio was 0.50, with an *f'c* of 24 MPa, a density of 1650 kg/m^3, and thermal conductivity of 0.45W/(m.k).

The results mentioned by the authors cited in their research are contrasted in Table 7.

RECYCLED WASTE AGGREGATES

The use of waste materials and byproducts to substitute natural or manufactured resources is considered a practical way of obtaining green construction materials (Grzeszczyk & Janus, 2020).

Tile waste aggregates

Awoyera, Olalusi, and Babagbale (2021) stated that, with the substitution of 100% of the sand with tile waste, and using ordinary Portland cement, in a cement/pulverized fine tile aggregate ratio of 1:3, an *f'c* of 17.97 MPa is obtained at 28 days, lower values than the control mixture made in said research, whose density was 2363 kg/m^3 and whose flexion resistance was 1.26 MPa.

Type of Aggregate	Type of Cement	Aggregate Percentage	Compressive resistance (MPa)	Density (Kg/m3)	Water/ Cement Ratio	Reference
Tile Waste A.	Ordinary Portland	100%	17.97	2363	---	(Awoyera et al., 2021)
Crushed Brick A.	CEM-I 42.5R	10%	31.5	2255	0.6	(Tareq Noaman et al., 2020)
	Ordinary Portland	100%	45	1920	0.48	(Yang et al., 2020)
	CEM I 52.5 N	10%	33	1845	0.39	(Atyia et al., 2021)

Table 8. Compressive resistance of recycled waste aggregates. Source: Prepared by the authors.

Crushed clay brick aggregates
The use of a minimum content of natural materials in concrete production is the main concern of many researchers. This is apart from the fact that lightweight aggregate concrete is desirable due to its low weight and its modified physical properties (Yao *et al.*, 2021).

In this way, Tareq Noaman, Subhi Jameel, and Ahmed (2020) used Portland CEM-1 42.5 R cement, for a w/c ratio of 0.6. With an optimal percentage of 10% crushed clay brick aggregate as a partial replacement of natural sand, a density of 2255 kg/m^3 was obtained, an *f'c* of 31.5 MPa, and water absorption of 7.93%.

Meanwhile, Yang *et al.* (2020) proposed the use of crushed bricks as a coarse aggregate to produce a new lightweight concrete. Ordinary Portland 42.5 grade cement was used in the process, with a w/c ratio of 0.48. As a result, a compressive resistance (*f'c*) loss of 12% to 25% was achieved, and a flexion resistance, of 9% to 22% at 28 days of curing. The sample that behaved best was the one that used 100% of the crushed brick aggregate, showing an *f'c* of 45 MPa, a flexion resistance of 7.5 MPa, and a density of 1920 kg/m^3.

The experimental results of Atyia, Mahdy, and Elrahman (2021) indicated that crushed brick aggregates can be reused as a replacement for normal-weight aggregates to obtain lightweight aggregate structural concrete, using Portland CEM I 52.5 N cement, and replacing 10% of the cement with crushed clay brick aggregate, with a w/c ratio of 0.39. This led to an *f'c* of 33 MPa, a density of 1845 kg/m^3, and thermal conductivity of 0.6 W/m.k.

A summary of the densities and resistances of the recycled aggregates mentioned in the results of the aforementioned research can be seen in Table 8.

OTHER TYPES OF AGGREGATES

Slate ceramsite aggregate
To produce lightweight concrete specimens, G. Zhang *et al.* (2021) used ordinary 42.5 Portland cement with a w/c ratio of 0.47 and an optimal slate ceramsite proportion of 25% to replace coarse aggregate. In this way, on testing said specimens in the laboratory, an *f'c* of 28.1 MPa was obtained, and a density of 1907 kg/m^3.

Granulated rubber aggregate
Pongsopha *et al.* (2021) considered Portland Type I cement, a granulated rubber aggregate, and the replacement of 10% of the coarse aggregate with a w/c ratio of 0.35. Here, a compressive resistance and a density of 20.8 MPa and 1904 kg/m^{3,} were obtained, respectively, along with a flexion resistance of 4.38 MPa. The thermal conductivity was 0.485 W/m°C.

Mud ceramsite aggregate
This technology reduces the harmful impact of solid waste on the environment and addresses the scarcity of natural resources. The goal of the study was to develop lightweight green concrete that incorporates sludge ceramsite. (J. Zhang, Wang, Ge, Yang & Wei, 2021).

In the same vein, Xie, Liu, Liu, Wang, and Huang (2019) determined that, on using ordinary Portland cement with a w/c ratio of 0.36 and substituting river sand for 40% mud ceramsite aggregate in volume, there is an *f'c* at 28 days of 13.63 MPa, and a density of 1251 kg/m^3. For this, they state that mud ceramsite is a more environmentally respectful material than normal concrete for non-load-bearing structures.

Steel fiber aggregate
In the research of Wang, Liu, and Guo (2021), Portland P 52.5 cement was used, with a w/c ratio of

Type of Aggregate	Type of Cement	Aggregate Percentage	Compressive resistance (MPa)	Density (Kg/m3)	Water/ Cement Ratio	Reference
Slate Ceramsite A	Ordinary Portland	25%	28.1	1907	0.47	(J. Zhang et al., 2021)
Granulated Rubber A	Portland Type I	10%	20.8	1904	0.35	(Pongsopha et al., 2021)
Mud Ceramsite A	Ordinary Portland	40%	13.63	1251	0.36	(Xie et al., 2019)
Steel Fiber A.	Portland P · 52,5	2.25%	63.1	1800	0.23	(Wang et al., 2021)

Table 9: Compressive resistance of other types of aggregates. Source: Prepared by the authors

0.23, and a 2.25% steel fiber content in replacement of the coarse aggregate. Its *f'c* at 28 days was 63.1 MPa, and its density was 1800 kg/m^3.

A new summary of the densities and resistances of other aforementioned aggregates can be seen in Table 9.

CONCLUSION

The following has been concluded, based on the opinions of the different authors revised in this work, and from the results of their research on the use of lightweight materials in concrete:

There are lightweight materials that, on being used as aggregates in concrete, cause the latter to lower its density. As such, they can be used in building high-rise constructions, as they reduce the structure's weight and, at the same time, improve the compressive resistance of the concrete.

The expanded clay aggregate had the highest compressive resistance, of 66.1 MPa, compared to the other materials used in manufacturing low-density concrete.

The concrete with the lowest density was manufactured with mud ceramsite aggregate, reaching a density of 1251 kg/m^3 and compressive resistance of 14 MPa, on using 40% mud ceramsite aggregate and a water/ cement ratio of 0.36.

The use of lightweight materials in concrete production is an environmentally friendly alternative solution, as it allows broadening the range of aggregates that can be used in concrete with similar characteristics to those of the conventional version. In this way, these will be contributing towards reducing the impact that the overuse of conventional gravel-based aggregates may cause, and the production of the greenhouse effect, both so harmful to the environment.

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MULTI-OBJECTIVE OPTIMIZATION OF ENERGY EFFICIENCY AND THERMAL COMFORT IN PUBLIC OFFICE BUILDINGS. CRITICAL SUMMER PERIOD IN THE CITY OF SAN JUAN -ARGENTINA[1]

OPTIMIZACIÓN MULTIOBJETIVO DE LA EFICIENCIA ENERGÉTICA Y EL CONFORT TÉRMICO EN EDIFICIOS DE OFICINA PÚBLICOS. PERIODO CRÍTICO DE VERANO EN LA CIUDAD DE SAN JUAN, ARGENTINA

Bruno Damián Arballo
Doctor en Arquitectura, Docente y Becario Postdoctoral CONICET, Instituto Regional de Planeamiento y Hábitat, Facultad de Arquitectura Urbanismo y Diseño, Universidad Nacional de San Juan. San Juan, Argentina
https://orcid.org/0000-0002-6121-549X
arballobruno@gmail.com

Ernesto Kuchen
Doctor en Arquitectura, Docente Investigador CONICET, Instituto Regional de Planeamiento y Hábitat, Facultad de Arquitectura Urbanismo y Diseño, Universidad Nacional de San Juan, San Juan, Argentina
https://orcid.org/0000-0001-6649-6932
ernestokuchen@faud.unsj.edu.ar

Daniel Chuk
Doctor en Ingeniería, Docente Investigador, Instituto de Investigaciones Mineras, Universidad Nacional de San Juan
San Juan, Argentina
https://orcid.org/0000-0003-3171-9571
dchuk@unsj.edu.ar

1 To the National Council of Scientific and Technical Research (CONICET). To the National University of San Juan.

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RESUMEN

El 40% de la demanda mundial de energía y de emisiones de CO_2 proviene de las edificaciones. En Argentina, los edificios son también responsables del 40% del consumo total anual de energía. El problema radica en el desequilibrio provocado entre la necesidad de proveer de una elevada calidad de vida y confort a los espacios de oficina y el costo de energía requerido para acudir a tal propósito. Tanto un alto nivel de confort como el ahorro energético representan dos objetivos a alcanzar. En ese sentido, este artículo propone una nueva metodología que combina la medición *in situ* con herramientas de simulación matemática. Se incorporan técnicas y modelos innovadores para la elaboración de la herramienta aplicando una optimización multiobjetivo termo-energética, que opera dinámicamente durante el horario laboral. Los resultados muestran un importante ahorro en el consumo energético para refrigeración de espacios de oficinas en verano (del 57,5% al 83,3%), junto con un aumento en la calidad del confort térmico de entre el 4,7% y el 29,4%.

Palabras clave
optimización en edificios, ahorro energético, confort interior

ABSTRACT

Buildings represent 40% of the world's energy demand and CO2 emissions. In Argentina, buildings are responsible for 40% of the total annual energy consumption. The problem lies in an imbalance between the need to provide a high quality of life and comfort in office spaces, and the high energy cost required to meet that goal. Both a high comfort level and energy savings represent two objectives to be achieved. In this sense, this paper proposes a new methodology that combines onsite measurement with mathematical simulation tools. Innovative techniques and models are incorporated to make the tool, applying thermal-energy multi-objective optimization, which operates dynamically during working hours. The results show significant savings in energy consumption regarding cooling office spaces in the summer, from 57.5% to 83.3%, together with an increase in the thermal comfort quality, with improvements between 4.7% and 29.4%.

Keywords
Building optimization, Energy savings, indoor comfort

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INTRODUCTION

Worldwide, buildings represent about 40% of energy use, naturally becoming potential scenarios for energy savings and emissions (Li, L. Zhang, Zhang & Wu, 2021; Abdou, Mghouchi, Hamdaoui, Asri & Mouqallid, 2021). The modern human being spends most of their time, from 80% to 90%, indoors (van Hoof, Mazej & Hensen, 2010). Multiple research projects have validated thermal comfort as one of the main variables that affect the comfort in indoor spaces and, in particular, the energy efficiency of buildings (Nguyen, Reiter & Rigo, 2014). Several international studies legitimize the perspective of adaptive thermal comfort as a key energy-saving strategy in buildings (Li *et al*., 2021; Sánchez-García, Rubio-Bellido, Marrero-Meléndez, Guevara-García & Canivell, 2017; Chandel, Sharma & Marwah, 2016), which leads to savings in the range of 30 to 60%, especially when the evolution of the outdoor climate is taken into account.

At a local level, analyses developed in the PICT2009-0014 Project Res.N°304/2010" "EEC, Energy Efficiency and Comfort in Workspaces" and doctoral studies (Arballo, 2020), in the city of San Juan, Argentina, substantiate the thermal dissatisfaction of inhabitants before their work environment and the potential of multi-objective optimization to improve energy efficiency and achieve important savings.

It is of particular relevance to consider the adaptability of inhabitants and onsite climatic variables in real-time, mainly the outdoor temperature (te), to delimit acceptance ranges (see Boerstra, van Hoof & van Weele, 2015). This database enables defining the variable thermal profiles needed to build models to control the indoor temperature of setpoints (Sp) (Rupp, Kim, de Dear & Ghisi, 2018; Rupp, Vásquez & Lamberts, 2015).

In this context, it is necessary to optimize building operation (EnBop, 2008) and develop a real-time multi-objective optimization between energy efficiency and the thermal comfort of inhabitants. These variables conflict since a significant energy saving in the air-conditioning system can result in indoor thermal discomfort conditions for inhabitants. In turn, the energy consumption of buildings depends significantly on the demands of the indoor environment, which affects health, performance, and comfort (Bliuc, Rotberg & Dumitrescu, 2007). The MOGA (Multi-objective Genetic Algorithm) genetic algorithms and the PSO (Particle Swarm Optimization), particle optimization algorithms are the most commonly used to optimize energy performance and comfort in buildings (Nguyen *et al*., 2014), due to their favorable characteristics and broad degree of applicability (Chambers, 2000). The mathematical theory of genetic algorithms, or MOGA, is presented in Coello, van Veldhuizen and Lamont (2002), and their application to the optimization of HVAC systems, in Lu, Cai, Xie, Li, and Soh (2005), and Atthajariyakul and Leephakpreeda (2005), among others. Genetic algorithms prove to be very useful when it comes to seeking an optimal solution of choice within a set of possible solutions in static situations (Stanislav, 2003). However, they have difficulties when defining possible solutions for dynamic control due to the randomness that their operations characterize. In the Argentine Coastal region, the Center for Computational Methods Research (CONICET-UNL, in Spanish) applies genetic algorithms (NSGA-II), using simulation (Building Energy Simulation) for the reduction of energy consumption (Bre & Fachinotti, 2017), as well as combining genetic algorithms with Artificial Neural Network Metamodels (Bre, Roman & Fachinotti, 2020).

Other less used and little tested algorithms, though they demonstrate very good results in dynamic situations (Y. Yuan, J. Yuan, Du & Li, 2012), are the heuristic ant colony optimization algorithms MOACO (Multiobjective Ant Colony Optimization). One of these is the MIDACO (Mixed Integer Distributed Ant Colony Optimization) algorithm, used to calculate space flight trajectories (Schlueter, Wahib & Munetomo, 2021). In this research, MIDACO is applied for the first time to the field of architecture.

METHODOLOGY

ONSITE COMFORT MEASUREMENTS AND MATHEMATICAL SIMULATION

The measurement methodology consists of conducting a systematic data collection procedure. To measure thermal comfort onsite, a HOBO U12-066 type temperature and humidity sensor (indoor temperature) is used, anchored to a mobile measuring device that moves inside the building (Arballo, 2020). At the time of the measurement, the mobile sensor is located in each office space, at 0.90 ± 0.20 m above floor level and at a radius not greater than one meter from the workplace of the evaluated inhabitant. This makes it possible to capture the environmental conditions perceived by them. This measurement provides objective thermal comfort data. A fixed UA-001-64 type outdoor rooftop sensor, allows recording the outdoor temperature. The operating temperature is considered as an average of the air temperature and the average radiant temperature ($t_{op} = \frac{t_a + t_{rm}}{2}$) (ISO 7730, 2005), considering that the air velocity remains below 0.2m/s and the difference

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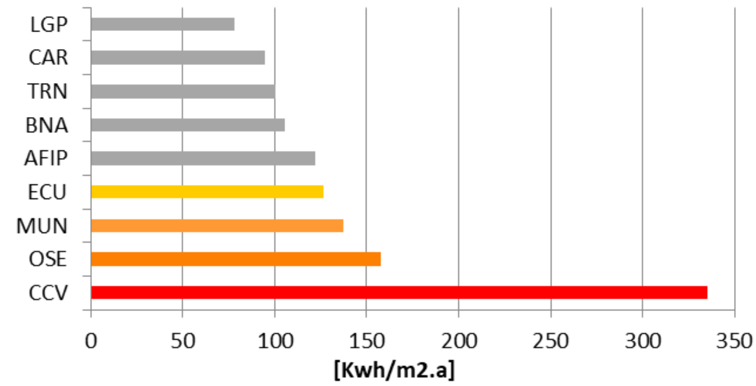

Figure 1. Annual electricity consumption in (kWh/m2.a), with office buildings in the civic intra-ring sector of the city of San Juan, Argentina, standing out. Source: EPRE (2017).

	I	II	III		IV
			A	B	
Name	CCV	OSE	MUN		ECU
Orientation	E-W	N-S	N-S	E-W	N-S
Surface area (m2)	80873	2455	4920		5320
Energy Consumption (Kwh/m2a)	335	158	137		126
Surveys	885	84	86	49	121

Table 1. Relevant information - case studies. Source: Arballo (2020, p. 48).

between air temperature and average radiant temperature is below 4K (Kelvin). In parallel to the measurement made with sensors, a comfort survey is made, which provides subjective information about the inhabitant regarding their workspace. Information on the comfort vote (CV) is obtained from the survey, based on a 7-point scale (ASHRAE Standard 55, 2004). Data on activity level (MET) and clothing (CLO) are also obtained, based on the ISO 7730 Standard. The measurement is carried out from Monday to Friday from 8 am to 1 pm in weeks that present climatic conditions.

CASE STUDIES

The four selected case studies (Figures 1 and 2) represent the highest percentage of annual electricity consumption (*Ente Provincial Regulador de Energía* [EPRE], 2017). They are located in the city of San Juan, Argentina (bioenvironmental zone IIIa, according to IRAM 11603, 2012), at an altitude of 630 meters, a latitude of 31.6° South, and a longitude of 68.5° West. They have a temperate warm dry climate, with an average annual outdoor temperature of 17.2°C, average relative humidity of 53%, high annual solar radiation of 2239.64 kW/m^2, 3300 hours of sunshine/year, high annual and daily thermal amplitude >14K (Kelvin), and winds from the south-east.

Based on these parameters, the main selection of the case studies corresponds to the following buildings (Table 1): I. Civic Center (CCV); II. State Sanitary Works (OSE); III. Central Building of the National University of San Juan (ECU); and IV. Municipality of the Capital (MUN).

The buildings have central air-conditioning equipment, except for the MUN building which is climatized with individual split-type air conditioning equipment. All have a sunshade system.

The CCV building has the largest percentage of public administration workers in the province of San Juan, with around 4,000 workers, and an average of 2,000 people who visit the building every working day. It is a systemic architecture, organized as a modular cell. The building structure is made up of reinforced concrete porticos. The scale of the building exceeds that of the city, and its characteristics are typical of those of architecture schools of the 1960s. The OSE and ECU buildings incorporated bioclimatic design criteria in the project stage, such as sunshades, a reduced window percentage, and 30 cm masonry to the north and west.

Optimización multiobjetivo de la eficiencia energética y el confort térmico en edificios de oficina públicos. Periodo crítico de verano en la ciudad de San Juan, Argentina
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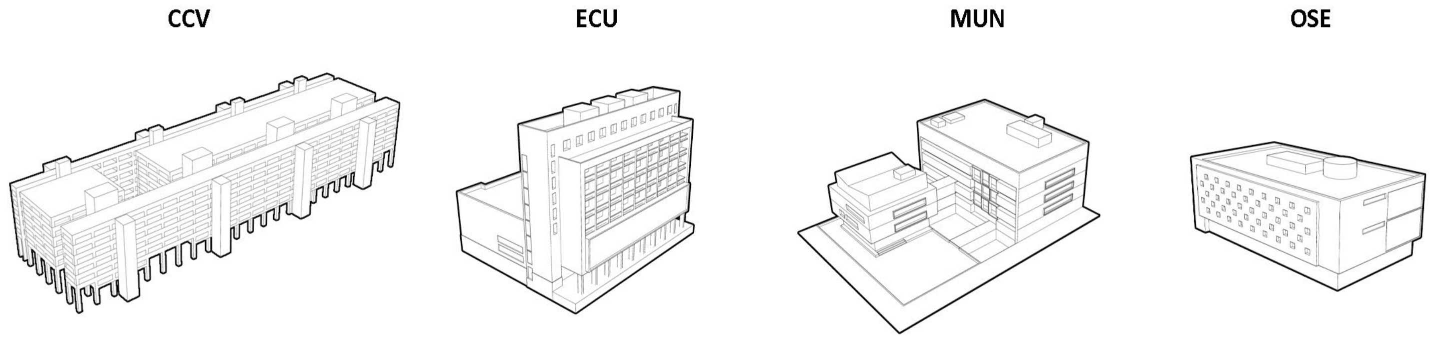

Figure 2. 3D layout of each building. Source: Arballo (2020, p. 62).

MULTI-OBJECTIVE OPTIMIZATION

Solving the problem of multi-objective optimization between energy efficiency and thermal comfort involves making the best decision considering a set of elements. In mathematics, optimization is related to obtaining the maximum or minimum of one or more evaluation functions of a system, where one speaks of single-objective or mono-objective optimization, and multi-objective optimization. In the latter, there are a series of evaluation functions that compete with each other, so one cannot talk about a single optimal solution value, but about a set of values that satisfy one or another objective to a greater extent. Said set of solutions can be found using the Pareto Optimality Criterion (Coello *et al.*, 2002).

From the real data based on measurements, the target functions are designed. The data matrices and the mathematical functions of the different variables are loaded into the MATLAB simulation program. The implementation of the multi-objective optimization algorithm, MIDACO, allows seeing the spectrum of possible solutions (Pareto Optimal Set), to which a preference selection is applied to reach the definitive optimum. Generally, the solution by "norm 2" or ideal vector is preferred to the utopia point.

The quantitative and qualitative evaluation of the results obtained leads to defining the energy efficiency proposals that entail an improvement in the inhabitants' quality of life (health and performance). The determination of the degree of applicability of the optimization proposals achieved thanks to this methodology, to cover energy and thermal demands, is carried out through qualitative analysis.

This multi-objective optimization is carried out in a standard/average space of each building in the most relevant period for the energy demand for air conditioning in the year: summer. By applying the optimization tool developed, the aim is to reduce the energy demand of each building by improving the comfort levels found. The thermal comfort value is expressed as *Diss* (% dissatisfied). The *Diss* variable is obtained from the thermal comfort model adopted (Kuchen, 2008). The energy demand variable, En, is marked in the figures with dotted lines on the x-axis.

DEFINITION OF THE MULTI-OBJECTIVE PROBLEM AND OBJECTIVE FUNCTIONS

At this point, the key variables that affect decision-making on the objective or evaluation functions in the course of the dynamic operation of the multi-objective optimization system, are defined.

The optimization setup assumes that there are two types of ventilation, both mutually exclusive:

a. Without air renewal: A ceiling fan that is capable of moving the air of the entire environment at a speed of V_a, without air coming in from outside. If the AA is off, the only influence is T_e.
b. With air renewal: A cross ventilation made up of two fans located inside using holes in exterior walls: One at one end of the room that blows air from outside and the second, at the opposite end, that extracts it. The result is an air movement with a speed of V_a, which brings in air from outside. The dynamic behavior is different from that of "a.".

The decision variables are updated at each "n" interval of the *k* sample. F is an input variable that differentiates the operating mode(s): F1, closed windows, AA off, ceiling fans move the air at a speed of *va*, as described in optimization setup "a."; F2, Operation of cross ventilation with outdoor air intake following optimization setup "b.", with

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air movement at speed V_a, and AA off; F3, AA on. Eventually, the ceiling fans described in "a." move the air.

Then, five evaluation functions are determined and all are related to the time space where the work schedule takes place. The decision variables are the air-conditioning setpoint - SPAA, the ventilation air speed, *va*, and the operation mode F. These variables are not static, but move throughout the operation period, usually 24 hours.

1. Energy demand:

$$f_1(\boldsymbol{x}) = E_n = \frac{\sum_{k=n_{w1}}^{n_{w2}} u_a(k)}{n_{w2} - n_{w1}} \quad (1)$$

This equation, $u_a \in \{0, 1\}$, is a binary control variable of AA that depends on the sequence designed by the optimizer for the setpoint of AA, SPAA, which is ON/OFF type. When the compressor of AA is working and, therefore, consumes energy, it is described as $u_a = 1$; otherwise, as $u_a = 0$. The n_{w1} and n_{w2} values correspond, in sampling intervals, to the start and end times of work, marked with vertical dotted lines on all the time graphs shown below. In this way, 0 < En < 1 is a measure of relative and dimensionless energy consumption. The consumption, *En*, will be the maximum possible - the unit - when the compressor is permanently working, $u_a = 1$ for all $n_{w1} < k < n_{w2}$ and, then, $= \frac{(n_{w2} - n_{w1})1}{n_{w2} - n_{w1}} = 1$. This measure makes it possible to easily compare different AA use strategies for the same environment and the same AA.

2. Average quadratic difference of the percentage of dissatisfied, *Diss*:

$$f_{2(x)} = \frac{\sum_{k=n_w(1)}^{n_w(2)} (Disc(k) - DiscObj)^2}{nw2 - nw1} \quad \forall\, Disc(k) > DiscObj \quad (2)$$

This is a function that, by its quadratic nature, reaches its minimum when for each sampling interval k, the percentage of *Diss*, dissatisfied, is equal to a certain target value *DissObj*, which is usually set between 7% - the admissible minimum of the Kuchen (2008) dissatisfied function - and 12%.

3. Control of temperature variations of the AA (air conditioning):

$$f_{3(x)} = \frac{\sum_{k=n_w(1)}^{n_w(2)} (SP_{AA}(k) - SP_{AA}(k-1))^2}{n_{w2} - n_{w1}} \quad (3)$$

This function (3), like the two consecutive ones, has the objective of stabilizing the oscillations of the air-conditioning setpoint, SPAA, by reducing the changes between one sampling interval and the next.

4. Control of variations in V_a (airspeed). Function (4):

$$f_{4(x)} = \sum_{k=n_w(1)}^{n_w(2)} (v_a(k) - v_a(k-1))^2 \quad (4)$$

5. Control of the number of changes in the operating mode F. Function (5):

$$f_{5(x)} = \sum_{k=h_w(1)}^{h_w(2)} (F(k) - F(k-1))^2 \quad (5)$$

6. Restriction function (6):

$$Disc(k) < DiscMax \ \forall \ h_w(1) < k < h_w(2) \quad (6)$$

This is the only restriction function implemented, and its purpose is that the instantaneous value of Diss never exceeds a DissMax limit that is always located above DissObj, for example, 15%.

RESULTS AND DISCUSSION

For the thermal comfort evaluation, the ISSO 74: 2014 Standard for class B buildings is considered, as defined in Boerstra *et al.* (2015) (Figure 3).

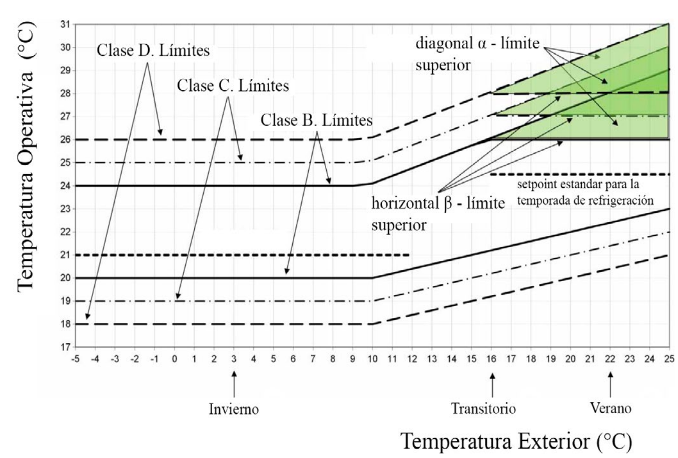

Figure 3. Requirements of ISSO 74: 2014 for operating temperature in relation to the outside temperature for Classes B, C, and D.
Source: Boerstra et al. (2015, p. 28).

According to the ISSO 74: 2014 Standard, all the workspaces of the CCV building are determined as type Beta (*β*) (Boerstra *et al.*, 2015). The expectation level of indoor thermal comfort is defined as normal, category B. 80% of the office spaces analyzed do not have access to opening windows (a fundamental strategy to restore personal comfort), and 100% of the spaces do not allow personally adjusting the thermostat. The average metabolic rate values (MET) are 1.35 (this is considered normal by ISSO 74). The CLO (clothing insulation) values have an average of 1.44 (values for normal office clothing regulations).

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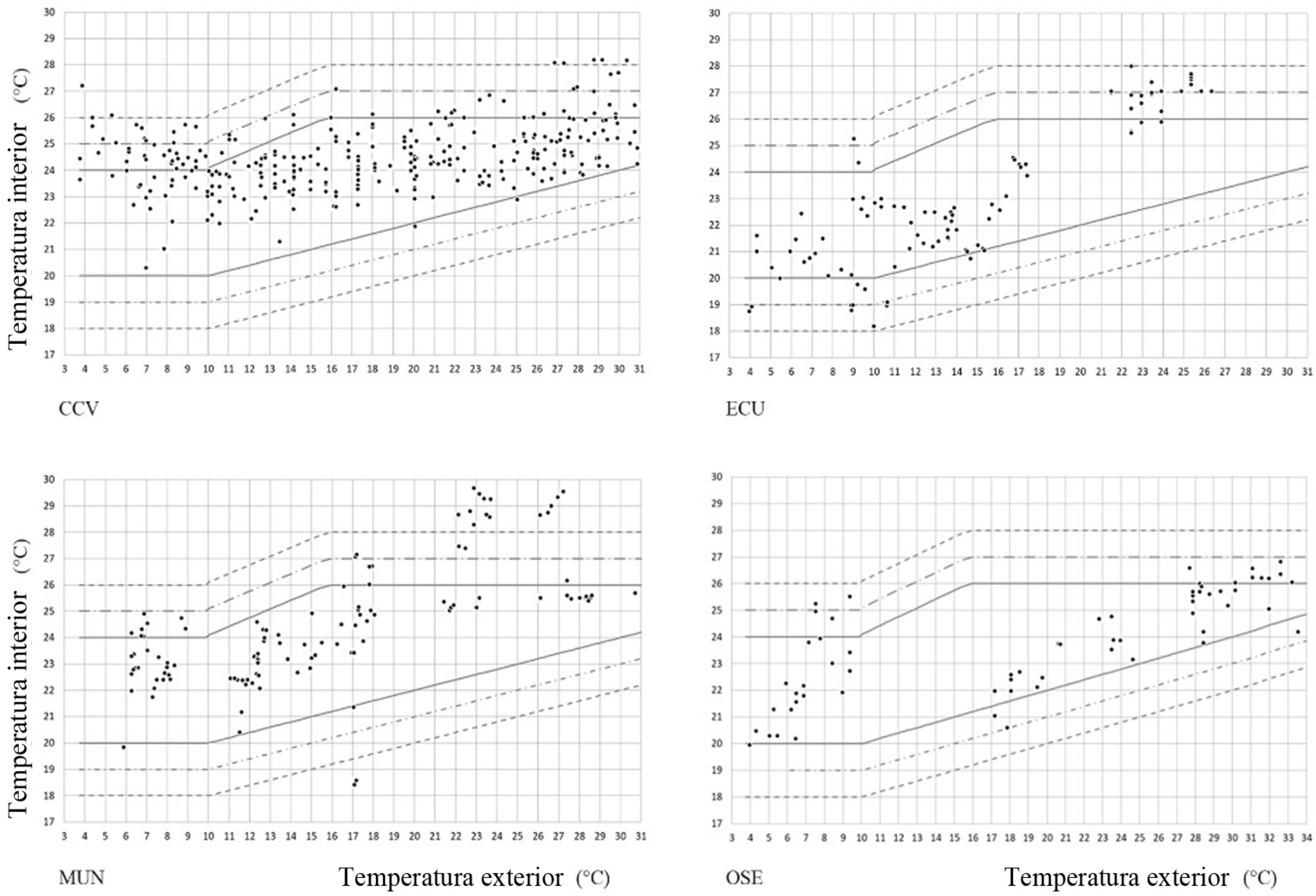

Figure 4. Thermal comfort evaluation for the annual period and comparison of buildings. Source: Arballo (2020, pp. 72-73).

In the annual data compendium (Figure 4) it can be seen that 70% of the data is included in the 90% acceptability area, complying with an average thermal comfort level based on the limits proposed by the ISSO 74: 2014 Standard for type β, class B office spaces.

For the case of the ECU building, the office spaces are determined as type β. The expectation level of indoor thermal comfort is defined as normal, category B. The office spaces have access to opening windows (a fundamental strategy to restore personal comfort), and 100% of the spaces cannot personally adjust the thermostat. In all spaces, the air conditioning system is clearly perceived. The average metabolic rate values (MET) are 1.40 (this is considered normal by ISSO 74). The CLO values (clothing insulation) are 0.76 for summer and 1.44 for winter (normal values for office spaces) (Toranzo, Kuchen & Alonso, 2012).

For the summer, 14% of the data are within class B (90% acceptability) and have an average percentage of acceptability of 86%. For the transitional period, 88% of the data match the class B area. For winter, 92% of the data responds to the class B area.

In the annual data compendium (Figure 4), it can be seen that 82% of the data are included in the 90% acceptability area, complying with the medium/high thermal comfort level according to the limits proposed by the ISSO 74: 2014 Standard for type β, class B office spaces. The summer is the most critical period of the year regarding the thermal acceptability of the inhabitants of ECU.

In the annual data compendium for the MUN building (Figure 4), it is seen that 78% of the data are included in the 90% acceptability area, complying with the average thermal comfort level, according to the limits proposed by the ISSO 74: 2014 Standard for office spaces of type β, class B.

For the case of the OSE building, the annual data compendium (Figure 4) shows that 85% of the data are included in the 90% acceptability area, complying with the medium/high thermal comfort level, according to the limits proposed by the ISSO 74: 2014 Standard for office spaces of type β, class B.

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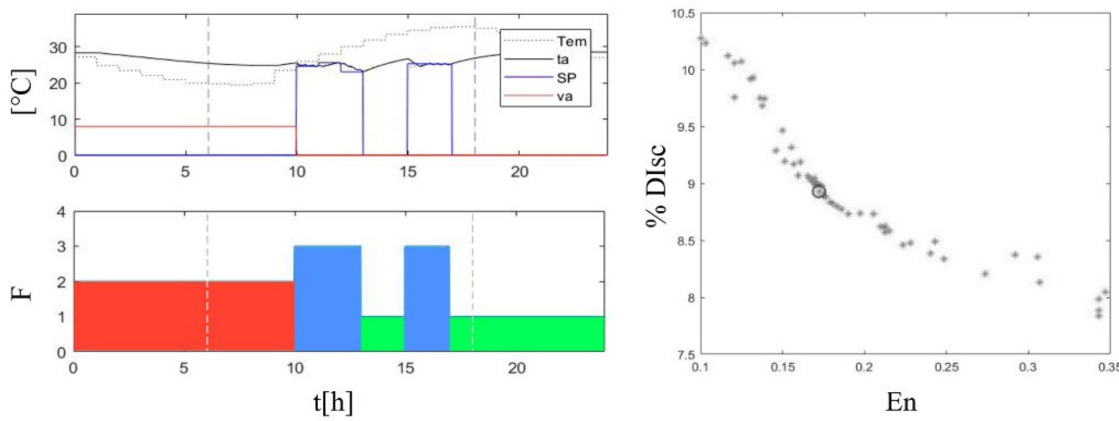

Figure 5. Left: Hourly evolution of operating modes F. Right: Pareto profile of Diss and En variables. Multi-objective optimization of a typical summer day in the CCV building. Source: Arballo (2020, p. 96).

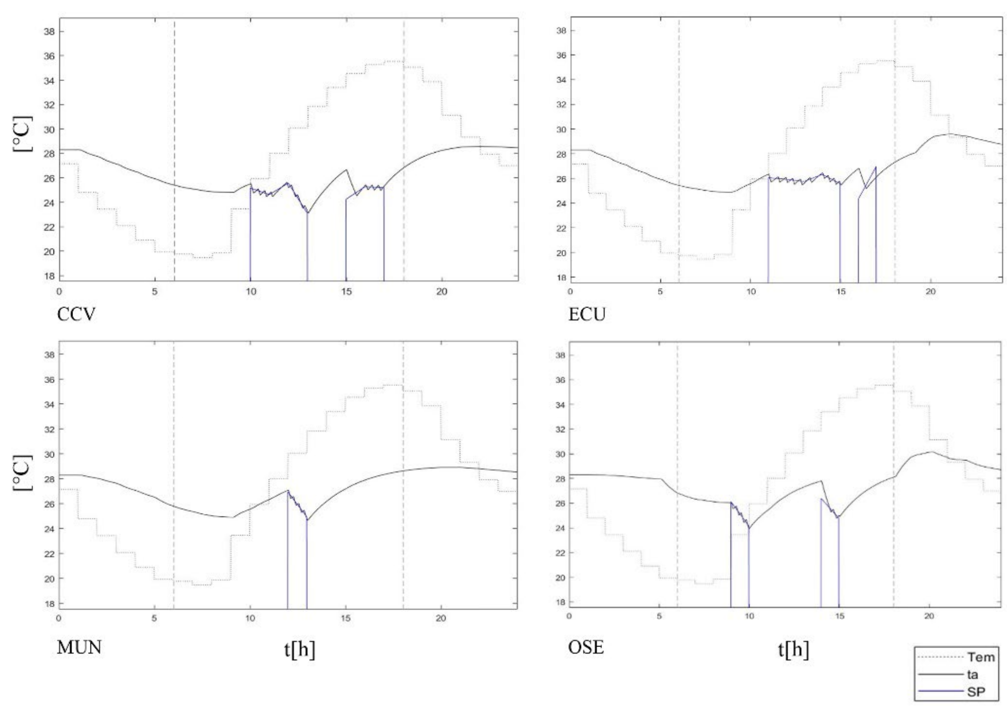

Figure 6. Hourly evolution of Tem (average outdoor temperature), ta (indoor air temperature), and SP (temperature of setpoint). Multi-objective optimization of a typical summer day for the four buildings. Source: Arballo (2020, pp. 97, 100, 104, and 107).

MULTI-OBJECTIVE OPTIMIZATION IN CCV

Figure 5 illustrates the optimization results for the case of the CCV building. According to the daily evolution, the system decides the *F2* (Window, red) strategy during the night (beyond this, it is not currently possible), until 10 AM the next day, when, due to the increase in outdoor temperature, the multi-objective optimizer changes to strategy *F3* (Air conditioning, blue).

In an intermediate segment of the work schedule, it is decided to move on to strategy *F1* (Envelope, green). This cut in the use of air conditioning (AA) allows considerable energy savings. Figure 6 shows, in detail, the evolution and relationship between the average outdoor temperature (*Tem*) and the indoor air temperature (*ta*). As noted, before 10 am, *ta* increases, leading to a change of strategy to *F3* (AA), with *ta*=26°C. With the use of AA, it decreases to *ta*=23.5°C. The system then turns the AA off and on again when *ta*=27°C (3 pm). Maybe during this time (strategy *F1* from 1 pm to 3 pm), even though the system defines this option as the most optimal one, this increase in temperature leads to narrow ranges of thermal acceptance for the inhabitants. However, this

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intermediate range in strategy *F1* does not imply energy costs, so it contributes to achieving significant energy savings.

These results are obtained from the optimal solution selection for Standard 2 (minimum distance to the ideal vector) found in the Pareto profile (Figure 5). For the CCV building, through optimization, *Diss*=8.85 and *En*=0.17 are achieved.

MULTI-OBJECTIVE OPTIMIZATION IN ECU

The work schedule is marked with dashed lines on the x-axis. In this case (Figure 7), the system decides the strategy *F2* during the morning, until 9 am; there are 2 hours of strategy *F1* and then it is modified to strategy *F3*. In a similar way to the case of the CCV building, it is decided as 1 hour - from 3 pm - of strategy *F1* (Figure 7).

At about 11 am, *ta* exceeds the 26°C limit (Figure 6), suggesting a change of strategy to *F3* (AA). With the use of AA, it decreases to *ta*=26°C. Then, the system proposes turning off the AA and turning it back on when *ta* it is approaching almost 27.5°C.

For the ECU building, through optimization, *Diss*=7.95 and *En*=0.12 are achieved. (Figure 7).

MULTI-OBJECTIVE OPTIMIZATION IN MUN

In this situation, the system advises the strategy *F2* during the morning until 10 am, then 2 hours of strategy *F1,* and finally, it is modified to strategy *F3*, which is maintained for 1 hour (Figure 8). In this case, the energy cost is minimal, compared to CCV and ECU.

With the use of AA, it decreases to *ta*=25°C. The system proposes turning off the AA 1 hour later, achieving significant energy savings. Towards the end of the working hours, *ta* reaches 28°C (Figure 6). Figure 7 shows the Pareto profile obtained based on the optimal selection preferred by Standard 2. For the case of the MUN building, through optimization, *Diss*=8.6 and *En*=0.05 are achieved.

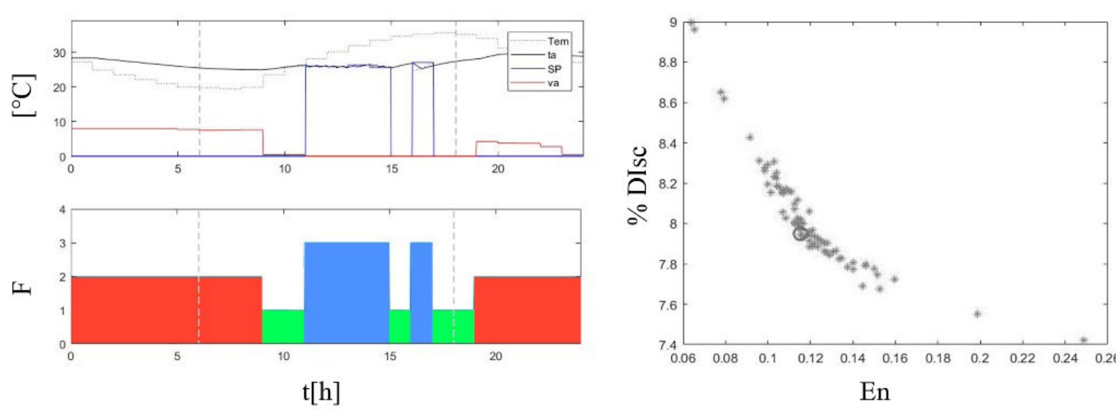

Figure 7. Left: Hourly evolution of operating modes F. Right: Pareto profile of variables Diss and En. Multi-objective optimization of a typical summer day for the ECU building. Source: Arballo (2020, p. 99).

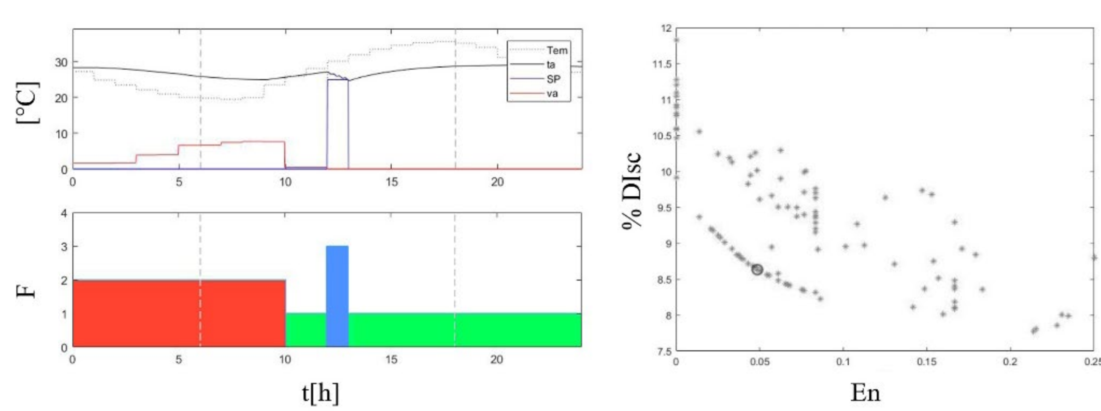

Figure 8. Left: Hourly evolution of operating modes F. Right: Pareto profile of variables Diss and En. Multi-objective optimization of a typical summer day for the ECU building. Source: Arballo (2020, p. 103).

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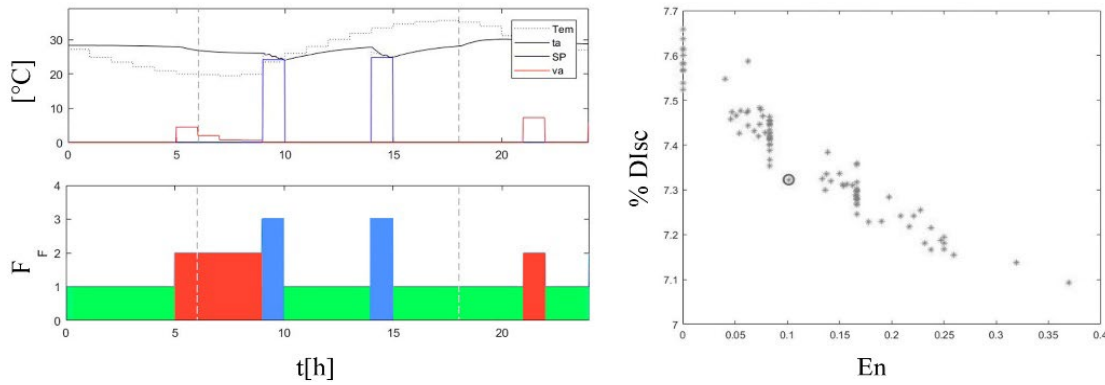

Figure 9. Left: Hourly evolution of operating modes F. Right: Pareto profile of variables Diss and En. Multi-objective optimization of a typical summer day for the ECU building. Source: Arballo (2020, p. 106).

	DISC			EN		
	MED	OPT	%	MED	OPT	%
MUN	38	8.6	29.40	0.3	0.05	83.33
ECU	35	7.95	27.05	0.4	0.12	71.25
CCV	14	8.85	5.15	0.4	0.17	57.50
OSE	12	7.32	4.68	0.3	0.10	66.67

Table 3. Improvements through Diss and En optimization (summer). Source: Arballo (2020, p. 108).

MULTI-OBJECTIVE OPTIMIZATION IN OSE

In the study situation of the OSE building, the system promotes strategy *F2* during the morning until 9 am. Until 3 pm, the system advises 2 hours of strategy *F3*, with an intervening 4-hour period in *F1* (Figure 9).

This is then modified back to strategy *F1*, which is maintained until the end of working hours.

At 9 am, the system is ahead of the increase in *ta* depending on *Tem*, requesting a change of strategy to *F3* (AA). With the use of AA, it decreases to *ta*=24°C (Figure 6). The system turns off the AA 1 hour later, achieving significant energy savings. Towards the end of the working hours, *ta* reaches close to 28°C. For the case of the OSE building, through optimization, *Diss*=7.32 and *En*=0.10 are achieved (Figure 9).

ANALYSIS OF THE RESULTS

This research shows (Table 2) that, when applying the proposed multi-objective optimization improvements in the *Diss* variable (greater thermal comfort) are obtained in all cases - for the summer -, with an average percentage of 20.53%. The normalized energy variable, *En*, also improves in all cases, with an average percentage of 69.6%. The results demonstrate that, through the implementation of the thermo-energy multi-objective optimization tool, the energy demand for the air conditioning of office spaces can be greatly reduced and, simultaneously, it can significantly improve the quality of thermal comfort.

From the classification of energy consumption according to items (for the summer), the consumption corresponding to the "cooling" item is determined (Table 3), which represents, for each building, the following percentages: CCV=45%; OSE=24%; MUN=12%; ECU=8% (Kuchen *et al.*, 2016).

There are energy benefit contributions of the thermo-energy optimization tool, achieving savings of up to 83.3% - in the case of the MUN building - of energy dedicated to cooling during the summer (Table 3). In this way, an energy-saving projection can be confirmed for the CCV building (building with the highest consumption in the province of San Juan), whose consumption is reduced in the cooling item in summer from 62 kWh/m^2 to 26.4 kWh/m^2 (cooling months).

For the buildings that consume the most and that were analyzed, the percentage of savings is reduced (57.5% and 66.7%), but for the buildings that consume the least,

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	Annual energy consumption [kWh/m2.a]	Summer energy consumption [kWh/m2.(summer)]	Cooling consumption [kWh/ m2.(summer)]	
			Without savings	With savings
CCV	335	137.5	62	26.4
OSE	158	71.1	17.1	5.7
MUN	137	50.7	6.1	1.0
ECU	126	56.9	4.6	1.3

Table 4. Consumption in summer according to each building and savings for the "air conditioning" item. Source: Arballo (2020, p. 108).

the potential savings are much higher, in the range of 71.3% and 83.3%. The ECU and MUN buildings consume the least, but at the cost of a higher average percentage (35% and 38%, respectively).

CONCLUSION

This research contributes to the creation of techniques and tools for architects, engineers, and specialists in the area, dedicated to the planning of new and existing buildings, which tend to compromise the use of (scarce) natural resources for operation, as well as the emission of greenhouse gases.

Knowing the sanitation advantages of existing buildings or, failing that, the creative solution possibilities in the development of new architectural projects, varying orientation layouts, ventilation, insulation and uses, namely, making the incorporation of bioclimatic concepts that are effective and necessary, positions the building sector on the verge of the change of the environmental paradigm in the reduction of emissions to the atmosphere.

In this work, the incorporation of techniques implemented for the first time in the architectural area of building energy retrofitting is highlighted, identifying design variables (natural/mechanical ventilation, air-conditioning power to be installed), and the control of indoor climate through MIDACO multi-objective optimization algorithms (ant colony). These contributions extend the range of optimization tools, in comparison with applications to office buildings in the project stage (thermal-energy simulation software, like, for example, Energy Plus, Trnsys, and others), which are revealed in the state-of-the-art, addressing the daily dynamic optimization for the retrofitting of existing buildings and future applicability to the development of smart control systems and definition of design guidelines (ventilation), in new buildings.

Specifically, the new design tool is validated by applying multi-objective optimization, where the gap between energy consumption and thermal comfort is reduced, achieving significant energy savings in the four case studies. The solutions found in the Pareto Sets allow contrasting the proposed hypotheses. The scope of significant electrical energy savings for air conditioning (cooling item) in the summer is highlighted, of between 57.5% and 83.3% savings, maintaining thermal acceptance percentages above 90% in all cases.

The design tool allows obtaining target values, that is to say, the definition of "design energy demands" values with a high level of daily detail and by workspace for the summer (in this case), introducing the operating temperature variables, outdoor temperature, and comfort level, in relation to energy consumption, that can be obtained through modeling in energy simulation software (Energy Plus or similar). This is validated in this work, focusing on office buildings with air conditioning in a dry warm temperate climate.

Currently, this research is associated with the technological development of a control system to dynamically optimize comfort variables and air conditioning/ventilation strategies in indoor spaces, in real-time. A State subsidy for the purchase of high-quality supplies and commissioning has been awarded.

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CONSTRUCTION WITH SOIL-CEMENT BLOCKS AS A SUSTAINABLE ALTERNATIVE FOR BUILDING ENVELOPES[1]

CONSTRUCCIÓN CON BLOQUES DE SUELO CEMENTO COMO ALTERNATIVA SOSTENIBLE PARA ENVOLVENTE EDILICIA

Adriana Belen Costantini-Romero
Arquitecta, Profesora Asistente, Universidad Nacional de Córdoba, Córdoba, Argentina
https://orcid.org/0000-0002-5164-0601
belen.costantini@unc.edu.ar

Franco M. Francisca
Doctor en Ciencias de la Ingeniería e Ingeniero Civil, Profesor, Universidad Nacional de Córdoba, Córdoba, Argentina
https://orcid.org/0000-0002-6965-9036
franco.francisca@unc.edu.ar

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RESUMEN

Los materiales alternativos, como los bloques de suelo estabilizado con cemento (BSEC), brindan nuevas oportunidades para realizar envolventes amigables con el medio ambiente. Los materiales de construcción realizados con suelo son fáciles de obtener y abundantes en la naturaleza, además de que su uso minimiza los impactos ambientales y mejora el comportamiento térmico de las edificaciones. En este trabajo se analizan las propiedades térmicas de los BSEC con el objeto de evaluar la eficiencia de los bloques para la construcción de envolventes. Se determina, mediante ensayos experimentales, que los porcentajes de cemento deberían ubicarse entre 3% y 9% para la fabricación de BSEC adecuados para mamposterías no portantes. El contenido de humedad debería ser inferior al 20%, a fin de evitar aumentos significativos en la conductividad térmica. A través de termografía pasiva se define también la resistencia térmica de los muros y las resistencias superficial interior y exterior mediante. Las distintas composiciones de muros con BSEC de una vivienda experimental en condiciones reales de uso se monitorearon durante época invernal y, a partir de ello, se establecieron transmitancias térmicas para los muros desde 1,219 W/m2K a 1,599 W/m2K. Los resultados obtenidos permitieron determinar la eficiencia relativa de los distintos tipos de envolventes para evitar pérdidas de calor.

Palabras clave
ladrillos sustentables, termografía pasiva en viviendas, reducción de pérdidas de calor, conductividad térmica, resistencia térmica superficial.

ABSTRACT

Alternative materials, such as cement-stabilized earth blocks (CSEB), provide new opportunities to make environmentally friendly envelopes. Earth-based construction materials are easy to obtain, abundant in nature, and their use minimizes environmental impacts and improves the thermal performance of bricks. In this work, the thermal properties of CSEB are analyzed, to evaluate their efficiency for building envelopes. It is experimentally determined that cement percentages are between 3% and 9% for the manufacturing of CSEB for non-bearing masonry. The moisture content should be less than 20%, to avoid significant increases in thermal conductivity. Wall thermal resistivity and inner and outer thermal resistance are also determined by means of passive building thermography measurements. The different CSEB wall compositions of experimental dwellings under real use conditions were monitored during the winter, and from this, thermal transmittances were established for the walls of 1,219 W/m2K to 1.599 W/m2K The results obtained allow determining the relative efficiency of each building envelope type in avoiding heat losses.

Keywords
sustainable bricks, passive thermography in buildings, reduction of heat losses, thermal conductivity, surface thermal resistance.

INTRODUCTION

Buildings are currently responsible for a large percentage of global energy consumption. The United Nations Environmental Program indicates that buildings, in fact, represent more than 40% (United Nations Environment Program [UNEP], 2009) of this. This energy expense generates between 25% and 30% of the annual CO_2 emissions and, therefore, constitutes between 10% and 12% of human contribution to climate change through the heat retained in the atmosphere. Facing this scenario, all technological improvements and the use of alternative construction materials that can reduce heat losses and gains in buildings have a very high potential impact on the reduction of greenhouse gas emissions, and the resulting global warming.

According to the Argentine National Institute of Industrial Technology, it could be said that approximately one-third of the energy generated in that country is consumed by buildings, and just under half of this energy is lost through thermal air-conditioning demand (INTI, 2005). From this amount, almost half is used to satisfy cooling and heating demand, and more than 30% of the rest is lost through roofs with poor quality thermal insulation, which leads to heat escaping in winter, and overheating in summer.

In Argentina, several standards define the thermal conditioning guidelines for buildings (IRAM N° 11549, 11601, 11603, 11604, 11605, 11507-4, 11900, 11659-1, and 11659-2). These guidelines establish the thermal values, among other design parameters, for the most commonly used construction materials. Among these parameters, density ρ (kg/m^3), thermal conductivity λ (W/mK), specific heat *cp* (J/kgK), and the water vapor diffusion resistance factor, μ (non-dimensional), stand out among the most important for heat flow. From these, it is possible to characterize construction materials to obtain the thermal transmittance *K* (W/m^{2}K), or the opposite, the thermal resistance *R* (m^2.K/W). It is important to consider that the thermal determinations are made under a stationary system, for which the most relevant parameter is the thermal conductivity λ of the material (Damfeu, Meukam & Jannot, 2016; Ouedraogo, Aubert, Tribout & Escadeillas, 2020).

The heat transfer mechanisms are conduction, convection, and radiation. The traditional envelopes of buildings are made, mainly, with solid materials with medium or low porosity, which are subjected to environmental temperature changes. The standards that regulate housing enclosures are mainly based on controlling heat transmission in the enclosures. As such, they consider the definition of the envelope's material and mass as priority (Dao, Ouedraogo, Millogo, Aubert & Gomina, 2018).

In recent decades, there has been a significant rise in the interest to get new materials for envelopes to make buildings more efficient from an energy point of view. Compressed stabilized cement-earth blocks (CSEB) are one of the alternatives explored, on being low-cost materials, whose manufacture is environmentally friendly as their use minimizes the carbon dioxide emissions generated by the traditional construction industry. CSEBs are manufactured with local earth and the addition of an aggregate (generally, cement and/or limestone), and water, which provides cohesion to the mixture and mechanical resistance to the masonry. This mixture is subjected to elevated pressure by mechanical compression, and unlike other masonries, it does not have any type of cooking process Nagaraj, Sravan, Arun & Jagadish, 2014; Costantini, Francisca & Giomi, 2021; Allen, 2012; Sekhar & Nayak 2018). Then, curing is done for at least 28 days. These blocks are a green economic and efficient alternative for buildings (Dahmen & Muñoz 2014; William, Goodhew, Griffiths & Watson, 2010).

The industrialization and construction with CSEB are limited by the lack of standards on the matter. There is a Standard that addresses the appropriate selection of earth and the construction with CSEB, with guidelines of principles and ways to build in countries such as Spain, France, New Zealand, and the United States, and in several regions of Africa. All these Standards are recommendations and directives of the CSEB production process (AENOR, 2008). Despite the advantages of using local earth and the lack of regulations in many countries, the use of CSEB for envelope construction has been noticeably increasing in recent times (Costantini, Carro Pérez, & Francisca, 2016). Recent studies showed that CSEBs with different soil types and a suitable stabilizing aggregate content exceed the mechanical resistance required by the traditional construction standards for seismic-resistant masonry (AENOR, 2008; Balaji, Mani & Venkatarama Reddy, 2016; Sitton, Zeinali, Heidarian & Story, 2018).

The heat flow through CSEB is considered, in general, as pure conduction, but heat transfer is also produced by radiation and convection. In porous mediums, such as compressed earth, the main form of heat transfer is conduction through solid particles (Yagi & Kunii 1957; Yun & Santamarina, 2008; Borbón, Cabanillas & Pérez, 2010; Mozejko & Francisca, 2020), given that the thermal conductivity of minerals is higher than that of the water and air found in the pores between particles. It is because of this that, among the factors that control the thermal conductivity of a material formed by particles, contact between said particles, density (or porosity), and the degree of humidification (or moisture content) are found (Costantini *et al.*,2021). Likewise, other secondary factors have an impact, to a lesser extent, in the heat transfers between porous mediums, such as the mineralogy of the particles, the particle size, and the pressure applied (Revuelta, García-Calvo, Carballosa & Pedrosa, 2021).

In the case of cemented earths, it is necessary to also consider the thermophysical properties of the stabilizing material incorporated, the curing time, and its thermal conductivity and calorific capacity (Costantin *et al.*, 2021). In CSEBs, heat flow is generally generated through solids (earth and cement particles), since the heat is transmitted more easily by conduction than through the air within the pores. As porosity increases (for example, in CSEBs with less density or holes), the thermal conductivity decreases, but the convection and radiation phenomena begin to gain relevance (Muñoz, Thomas y Marino, 2015; Balaji & Mani, 2019).

The use of techniques like thermography allows rating the energy efficiency of constructions, detecting construction issues, thermal bridges, lack of water tightness, and heat losses, through thermal contrasts where specific defects and pathologies can be differentiated (Sharlon, 2008; Fox, Coley, Goodhew & de Wilde, 2014). The experiences reported in specialized literature have shown the suitability of thermographic analysis to quantify the efficiency of insulation systems, detecting preference heat flow paths, air losses, and mapping moisture content (Grinzato, Vavilov & Kauppinen, 1998). One of the main advantages of thermography in housing is that it allows measuring surface temperatures non-invasively. Starting from these measurements, it is possible to perform qualitative analysis, differentiating building areas and different materials (Revillas, 2011). This also facilitates quantifying heat losses through an envelope and defining the thermal transmittance coefficient of each one of the walls a building is made up of (Sekhar & Nayak, 2018; Muñoz *et al.*, 2015).

In particular, the purpose of this work is to evaluate the thermal behavior of compressed cement-earth blocks used to build envelopes in an experimental dwelling. In this sense, different wall types are analyzed in the dwelling to determine the thermal transmittance of each composition with CSEB and the surface thermal resistances (interior and exterior), to determine the efficiency of each envelope.

METHODOLOGY

Initially, the thermal conductivity of the cement-earth blocks is characterized in the laboratory, and the thermal properties of the construction materials, used for the analysis of the results, are defined. Then, a building is monitored using HOBOs and a thermographic camera, determining temperature variations and thermal bridges with a qualitative and quantitative analysis of the surface temperatures of the envelopes. After this, an analysis of the Argentine IRAM Standards, and of the requirements of suitable comfort for building envelopes, is made. From this, the admissible surface resistance and wall thermal transmittance values are analyzed, determining the minimum values to reach thermal comfort considering the bio-environmental zone. In this way, the surface thermal resistances are calculated to define the heat losses of each envelope typology configured with cement-earth blocks, in real use conditions and in winter.

THERMAL CONDUCTIVITY MEASUREMENT

The thermal conductivity of the cement-earth masonry of the envelope is made using an East 30 Sensor. The experimental procedure, and the methodological details of this technique, fall under the ASTM D-5334 Standard. Before testing the bricks, the measurement needle is calibrated, and the values measured with the thermal conductivity of materials with known properties are compared. Distilled water and liquid glycerin are used for the calibration. This process results, in the case of the first material, in a value of 0.595 W/(m K), for a theoretical value of 0.607 +/- 0.03, and of the second one, a value of 0.293 W/(m K), for a theoretical value of 0.292 +/-0.003. It is worth highlighting that the percentage errors are less than +/- 3%:

The CSEBs are 25 cm long, 12.5 cm wide, and 7 cm tongue-and-groove prisms. They have two 7 cm diameter holes on the side that are used for their installation inside the wall. To measure the thermal conductivity of the CSEBs, the 1 mm diameter, 60 mm long stainless-steel needle sensor is introduced into a hole drilled in the blocks. The hole is made of a diameter that is slightly larger than that of the sensor, so that the needle can enter. The position of the hole is chosen carefully to avoid that the presence of air chambers produces border effects that could affect the measured results.

Once water is inserted, a direct current is applied using an Agilent E3645A voltage generator, which produces heating since a conductor thread is lodged inside the needle. The heat generated dissipates through the medium in contact with the needle,

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through a thermocouple of 0.01°C accuracy at the heart of the needle, which detects the temperature changes over time. This measurement is made with an Agilent 34410A multi-meter. Starting from the temperature changes over time, an inverse analysis is made to calibrate the solution of the axisymmetric heat flow equation, and thus determine the thermal conductivity of the material around the needle. Figure 1 presents a standard result where the temperature increase caused by the heating the needle over time can be seen, as well as the curve sector used to approximate the theoretical solution to the experimental results, following the guidelines suggested in the ASTMD-5334 Standard.

The temperature monitoring time ranges between 60 and 120 seconds, during which care is taken that the temperature increase of the sensor does not exceed 3°C. All the tests are made under controlled temperature and humidity conditions of 24°C and 50°, respectively. Each test was repeated at least 6 times, to then adopt the average of the measurements as a representative value.

THERMOGRAPHIC ANALYSIS

Images were taken using a TESTO 871 thermographic camera, with an IR resolution of 240 x 180 pixels, field of vision of 35° x 26° / 0.5m, spatial resolution 1.6 mrad, thermal sensitivity 90 mK, measurement frequency 9Hz, temperature range of -30°C to 650°C, and precision of 2°C ±2 % of the value measured.

During the measurements, an emissivity equal to 0.95 and a background reflected temperature compensation of 20°C, were adopted as the setup of the camera, following the recommendations of the infrared thermographic guide (Revillas, 2011). The thermographic images were taken at 4 different moments of the day, with overcast weather to avoid direct solar radiation on the external images of the dwelling. Using these images, a daily average surface temperature of each wall type was determined. This procedure allowed obtaining indoor images in a minimum time difference and thus knowing the indoor-outdoor temperature difference within short periods (not more than 1-minute differences). After the analysis and processing of the thermograms, the surface resistance of the walls was determined, using their thermal resistance and heat flow calculations.

To calculate the surface thermal resistance, the properties of the surface, emissivity, airspeed along the surface, and the surface, ambient air, and surrounding surface temperatures were used. In this way, the RS surface thermal resistance on flat surfaces resulted in (AENOR, 2008)

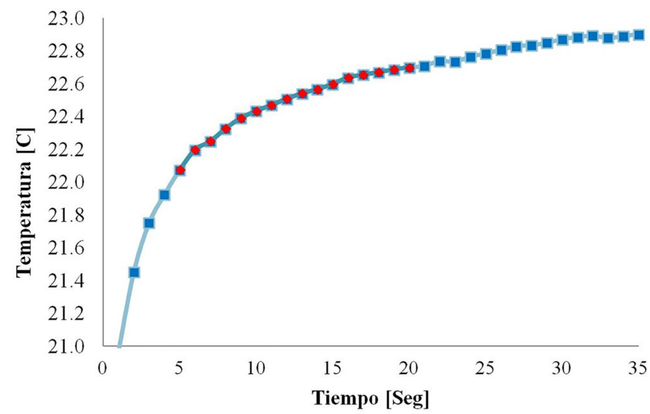

Figure 1. Standard temperature change response of the needle over time, during the thermal conductivity measurement. Source: Prepared by Francisca and Costantini Romero.

$$Rs = 1/(hc+hr) \quad \text{......................(1)}$$

Where *hc* is the convection coefficient and *hr* is the radiation coefficient. The convection coefficient, in the case of horizontal heat flow, was 2.5 W/(m^2K) on the indoor surface, and 20 W W/(m^2K) on the outdoor one, as per the IRAM Standard (1996). On the other hand, the convection coefficient was determined as follows:

$$hr = \varepsilon \, hr_0 \quad \text{......................(2)}$$

Where ε is the emissivity coefficient and *hr0* is the radiation coefficient for a black body, as follows:

$$hr_0 = 4\,\sigma\,Tm^3 \quad \text{......................(3)}$$

Where σ = 5.67 x 10^{-8} W/m^2K^4 is the Stefan-Boltzmann Constant, and *Tm* is the thermodynamic mean temperature of the surface and its surroundings. Following equations (1) to (3), *Rs* was:

$$Rs = 1/(hc + \varepsilon\, 4\, \sigma\, Tm^3) \quad \text{.............(4)}$$

EXPERIMENTAL DWELLING

The proposed methodology was applied to the study of the facades of the second floor of an experimental dwelling located in the city of Alta Gracia, in the Province of Cordoba, Argentina, which is shown in Figure 2. The dwelling has two floors and only the top floor is built with compressed cement-earth blocks (CSEB). The particularity of this dwelling is that, on the entire top floor, built with a traditional or wet system, different types of coatings were used on the envelope walls. This dwelling is residential.

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Figure 2. Experimental dwelling: a) East façade; b) West façade. Source: Preparation by Costantini Romero.

The evaluation of the thermal behavior of the building was carried out with the continuous record of temperature and humidity for 7 days in August, from Friday, August 9th, to Friday, August 16th, 2019. In this period, the trends of the results obtained were similar.

Figure 3 shows the top floor of the dwelling under study, with the position of the sensors installed, and the description and location of walls being studied. As can be seen, the temperature and humidity sensors are in the living room, in one of the bedrooms, and outside the dwelling. The monitoring of the environmental conditions was made using the installation of a HOBOtemp and the storage and recording of the data with an RH logger. 2 HOBOs were placed inside the dwelling at a height of 1.50 m from the floor, and one on the outside. This allowed obtaining the real temperature of the environment with values recorded every 60 minutes.

The temperatures recorded oscillated between 2°C and 32°C, while the outdoor relative humidity was between 15% and 75°. Table 1 presents the outline and a description of the setup of each one of the walls analyzed in the experimental dwelling.

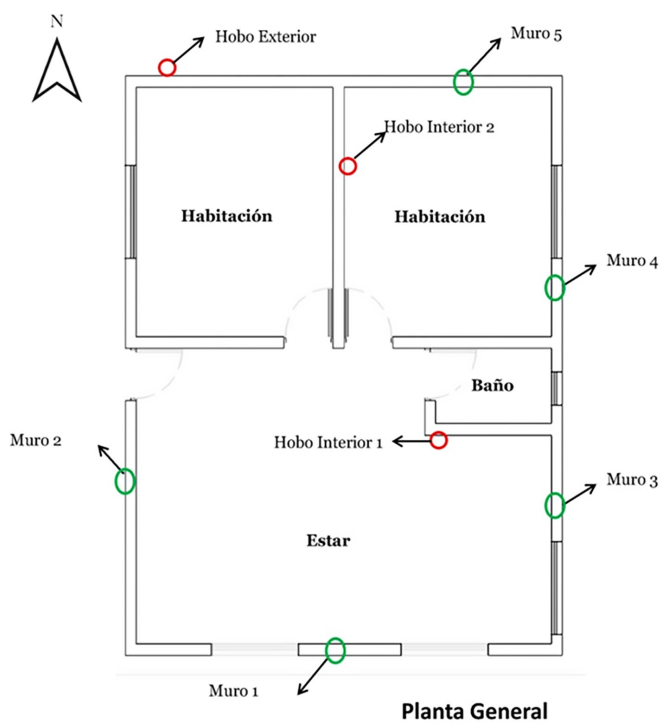

Figure 3. General floorplan of the dwelling with the HOBO layout and wall designation. Source: Preparation by Costantini Romero.

THERMAL RESISTANCE AND HEAT FLOW

The heat flow by area unit [W/m²] through the building envelope can be calculated as:

$$q = K\,(Te - Ti) \quad \text{......................(5)}$$

Where *K [W/(m² K)]* is the thermal transmittance of the masonry, and *Te* and *Ti [K]* are the outdoor and indoor temperature, respectively. As these are exterior envelopes, the *K* value is obtained by the resistance of heat *R* passing through, bearing in mind that this is a heat flow problem perpendicular to the wall layers, resulting in:

$$R = 1/K = Rsi + \sum_i e_i/\lambda_i + Rse \quad \text{......................(6)}$$

With e_i *[m]* is the thickness of each wall component layer; λ_i *[W/(m K)]* is the thermal conductivity of the material of each wall layer; *Rsi [m² K/ W]* is the internal surface thermal resistance; and, *Rse [m² K/ W]* is the external surface thermal resistance.

In equation [6], the thermal conductivity of each layer was obtained from the current Argentinian Standard, IRAM 11601. In the case of the CSEBs, this was calculated using the measurements of the material's λ, the geometry (12.5 cm x 25 cm x 7 cm), and the 2, 7cm diameter air chambers located symmetrically and equidistant from the block's walls. For the case of the air, λair = 0.165 W/m K was considered, a value obtained from the IRAM Standard [4].

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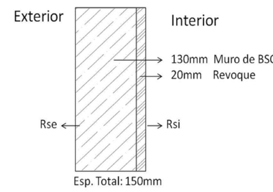
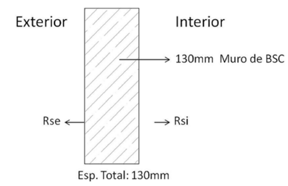
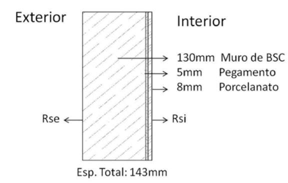
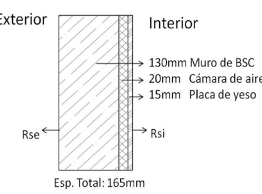
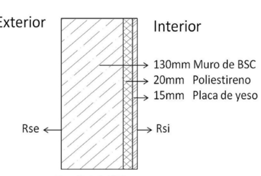
Wall	Wall Type	Layout and Description
Wall 1	Coated cement earth	
Walls 2	Cement earth	
Wall 3	Cement earth with porcelain tile	
Wall 4	Cement earth with plasterboard	
Wall 5	Cement earth with plasterboard and polystyrene	

Table 1. Main characteristics of the tested walls. Source: Preparation by Costantini Romero

RESULTS AND DISCUSSION

THERMAL CONDUCTIVITY OF CSEBS

The conductivity values were obtained through tests in 10 CSEBs. These measurements allowed defining the thermal conductivity of the solid fraction of the CSEBs, that is to say, of the compressed cement-earth. Using these measurements, an average and a standard deviation were calculated for the compressed cement earth: $\lambda = 0.347 \pm 0.021$ W/mK. Then, the equivalent thermal conductivity of the CSEB was analytically determined, considering the geometry of the block and the presence of air chambers shown. In this way, a thermal conductivity of $\lambda_{CSEB} = 0{,}283$ W/m K was obtained for the CSEB.

The difference between the thermal conductivity of the block material (compressed cement earth) and the block itself ($\lambda = 0.347$ W/mK in the former and $\lambda_{CSEB} = 0.283$ W/mK in the latter) reflects the importance of the holes and the thermal bridges, as practically the entire heat flow in the CSEB would be passing through the nerves, despite 46% of the transversal section being interrupted by the air chambers.

INDOOR AND OUTDOOR SURFACE RESISTANCES

The surface resistances are calculated using the indoor and outdoor temperatures of the surface of each wall selected. Figure 4 presents thermograms of the outside walls of the experimental dwelling. The thermograms show the temperature differences of the different construction materials, differentiating the thermal bridges and highlighting the thermal gains and losses through the envelope. The emissivity of the different materials (mainly inside), shows that the *Rse* should be different to calculate the thermal conductivity of each wall typology.

The indoor and outdoor surface thermal resistances were obtained using equation [4], considering the surface mean

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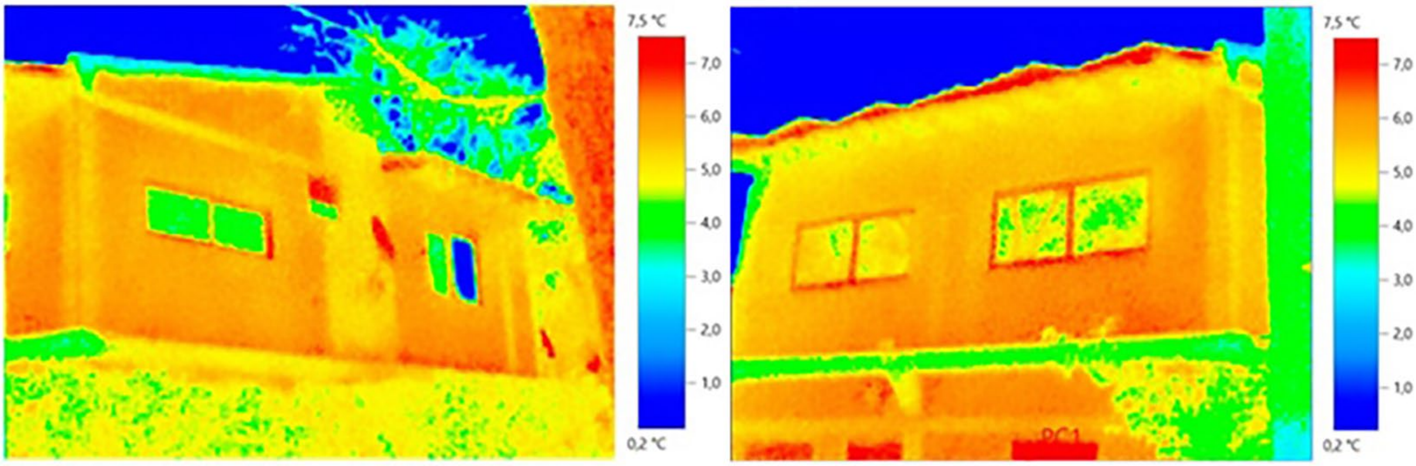

Figure 4. Outdoor thermographic images. Source: Preparation by Costantini Romero.

temperatures *Tm* determined by the thermograms and the emissivity coefficients, ε, established in the AENOR (2008) Standard for the different surface types. The results attained for each wall type are presented in Tables 2 and 3.

The values obtained are very close to those recommended in the Argentinian Standard, which establishes the following values for internal and external surface thermal resistance: *Rsi* = 0.13 m^{2}K/W and *Rse* = 0.04 m^{2}K/W, respectively. In both cases, these values correspond to the vertical walls with a horizontal heat flow. It is also seen that the variation throughout the day is negligible for all purposes. It is important to underline the importance of determining experimentally the *Rsi* and *Rse* values, to have more information about the energy efficiency of the enclosures and, therefore, of the buildings. The adoption of standardized values would not be advisable and could lead to significant deviations in the heat losses estimated for the dwellings.

HEAT FLOW

The heat flow is defined considering the composition and typology of each of the 5 walls of the envelope of the dwelling under study, the average *Rsi* and *Rse* calculated in Tables 2 and 3, and the thermal conductivity of the CSEB determined experimentally. The results, in this sense, are presented in Table 4. It is seen that, in these, the thermal transmittance of the walls decreases as insulating elements such as air chambers, polystyrene, or plaster are included, adding to or increasing the thermal resistance of the set. Walls 4 and 5, with transmittance *K* = 1.219W/m^{2}K and 1.251 W/m^{2}K, are not only the most thermally resistant, but also reach the values that the

Wall	Wall Surface	Time of the Day				Rsi (m^{2}K/W)
		00:00	06:00	12:00	18:00	Average
Wall 1	Varnished (ε=0,85)	0,147	0,148	0,146	0,142	0,146
Wall 2	Varnished (ε=0,90)	0,142	0,143	0,141	0,136	0,141
Wall 3	Varnished (ε=0,95)	0,137	0,138	0,136	0,132	0,136
Wall 4	Varnished (ε=0,80)	0,153	0,154	0,152	0,147	0,152
Wall 5	Varnished (ε=0,93)	0,139	0,140	0,138	0,133	0,138

Table 2. Indoor surface thermal resistance (Rsi) for each wall type.
Source: Preparation by Costantin Romero

Wall	Wall Surface	Time of the Day				Rsi (m^{2}K/W)
		00:00	06:00	12:00	18:00	Average
Wall 1	Varnished (ε=0,85)	0,041	0,041	0,040	0,040	0,041
Wall 2	Varnished (ε=0,85)	0,042	0,041	0,041	0,041	0,041

Table 3. Outdoor surface resistance values (Rse) for each wall type.
Source: Preparation by Costantini Romero.

Wall	Element layer	Thickness (m)	λ(W/mK)	R (m^2K/W)	K (W/m^2K)
Wall 1	Rsi	-	-	0.1460	1.499
	2- Brick	0.1300	0.283	0.3662	
	3- Interior coating	0.0200	0.960	0.0208	
	Rse	-	-	0.0410	
	Total thickness	0.15	Total Resistance	0.6672	
Wall 2	Rsi	-	-	0.1410	1.599
	2- Brick	0.1300	0.283	0.3662	
	Rse	-	-	0.0410	
	Total thickness	0.13	Total Resistance	0.6414	
Wall 3	Rsi	-	-	0.136	1.473
	2- Brick	0.13	0.283	0.3662	
	3- Mortar	0.005	0.160	0.031	
	4- Porcelain Tiles	0.008	0.700	0.011	
	Rse	-	-	0.041	
	Total thickness	0.143	Total Resistance	0.679	
Wall 4	Rsi	-	-	0.152	1.219
	2- Brick	0.13	0.283	0.3662	
	3- Air Chamber	0.02	0.165	0.125	
	4- Plasterboard	0.015	0.347	0.043	
	Rse	-	-	0.041	
	Total thickness	0.165	Total Resistance	0.821	
Wall 5	Rsi	-	-	0.138	1.251
	2- Brick	0.13	0.283	0.3662	
	3- Polystyrene	0.02	0.170	0.118	
	4- Plasterboard	0.015	0.347	0.043	
	Rse	-	-	0.041	
	Total thickness	0.165	Total Resistance	0.799	

Table 4. Thermal transmittance values for each masonry typology. Source: Preparation by Francisca and Costantini Romero.

IRAM Standard establishes to be recommended in the efficient construction under summer conditions, where the Standard sets a maximum value of 1.80 W/m^{2}K. However, for winter, none of the envelopes should exceed the minimum value required, of 1.00 W/m^{2}K, since the requirements are more rigorous.

The air chambers incorporated in the masonry, materialized through the plasterboards, improve the thermal behavior of the walls, reducing the heat flow by almost 25%. The drop in *K* is significant compared to that of a simple masonry wall with CSEB. In the walls with air chamber and plastic, and with a polystyrene and plaster aggregate, considerable efficiency improvements were observed. The results of this research present, as can be seen, an experimental database to validate heat transfer models in walls. These results show the advantages of using earth as a sustainable building material.

CONCLUSION

In the work outlined here, the thermal properties of compressive cement-earth bricks were evaluated as a sustainable alternative for the construction of building envelopes. In this framework, the main thermal properties of bricks and their application in an experimental dwelling were examined, where the top floor was built with compressed cement-earth walls with different construction technologies for the enclosures. The heat losses were analyzed for each alternative and, finally, the advantages of adopting this type of bricks for the construction of high thermal efficiency facades were determined. The main conclusions of the study are summarized as follows:

- The analysis of the thermal transmittance of five types of structured walls of different built forms, using compressed cement-earth blocks, allows confirming that the bricks used are an excellent alternative to materialize constructions with a low environmental impact, since their use minimizes the indoor heat gains and losses during summer and winter, respectively.
- The passive thermography was a non-invasive and low-cost method by which it is possible to detect the surface temperatures of each wall. Thus, the indoor and outdoor surface resistances of an envelope wall are obtained directly, which opens the option to develop a suitable design for the thermal conditioning of a building. Having a direct measurement of the surface thermal resistances allows increasing the accuracy in the determination of heat losses in buildings, experimentally determining the thermal conductivity of the masonry material and the *Rsi* and *Rse* surface resistances of the envelope's coating.
- The thermal transmittance of each wall typology varies depending on the resistance to heat passing through that each masonry offers. For the different walls evaluated, values between 1.219 and 1.599 W/m^{2}K were obtained, which are within a suitable range for summer, considering the Argentinian Standard. The analysis method followed in this work can be applied to dwellings built with other construction techniques and in different locations, but always making sure to compare the thermal transmittances obtained with the local regulations.
- The surface resistances vary with each type of material and throughout the day, as such their direct determination is recommended instead of just adopting standardized values. Regarding the walls tested, the values obtained range between 0.138 and 0.152 m^{2}K/W, for internal resistance, and 0.041 m^{2}K/W for the external one. The adoption of values that are suitable for the reality, allows adapting envelope designs and material use to save energy in the thermal conditioning of dwellings. Likewise, it is worth stating that the procedure proposed and carried out in this research is applicable to any construction typology, and to buildings in any bioclimatic region in any country. It is recommended to adopt the procedure proposed here and to compare the results obtained with the local regulation of each country.
- The results analyzed, show the importance of having quantitative heat flow determinations after building a dwelling. This allows considering, directly and concretely, the location in the energy consumption calculation for thermal conditions, and also designs that match the real conditioning needs, to achieve thermal comfort in the buildings.

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