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DIRECCIÓN:
Avda. Collao 1202
CP: 4081112. Concepción, Chile
TEL.(56-41)3111409

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Editorial
Maureen Trebilcock-Kelly
Revista Hábitat Sustentable Vol. 14, N°. 1. ISSN 0719 - 0700/ Págs. 04 - 07
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EDITORIAL

Me complace introducir este número de la revista Hábitat Sustentable compartiendo la buena noticia del avance de la revista hasta el cuartil Q2 en el ranking Scimago, área de Arquitectura. De esta manera, la revista se posiciona en el número 64 dentro de 179 revistas del área, principalmente por el número de citas que recibe cada uno de sus artículos, entre otros criterios de cobertura e impacto. Si consideramos solo las revistas indexadas en Scopus de la región Latinoamericana, HS se posiciona en el segundo lugar, tanto en el área de Arquitectura como de Construcción. Este logro se debe al arduo trabajo que realiza el equipo de gestión editorial encabezado por Jocelyn Vidal, así como a los investigadores e investigadoras que componen el comité editorial y el grupo de pares revisores.

Uno de los principales méritos de HS es pertenecer al grupo de revistas denominadas de "acceso abierto diamante", lo que implica que sus artículos son publicados sin costo para autores y lectores. En tiempos en que la mayoría de las publicaciones científicas se concentran en grandes editoriales internacionales con fines de lucro, resulta motivante para la comunidad académica contar con una revista con las características de HS. Esto es posible gracias al compromiso que la Universidad del Bío-Bío (Chile), a través de la Facultad de Arquitectura, Construcción y Diseño y la Vicerrectoría de Investigación y Postgrados, ha tenido en pos de promover el acceso abierto a resultados de investigación.

Durante el año 2023, con el fin de aumentar la visibilidad de los artículos, hemos creado cápsulas audiovisuales que resumen cada artículo publicado, las cuales se difunden en las redes sociales de la revista, tales como Instagram y LinkedIn. De esta forma, los resultados de la investigación académica pueden alcanzar no solo el medio académico, sino también el público general.

Dentro de los desafíos futuros, nos parece importante atraer a autores y autoras que estén generando conocimiento avanzado en temáticas de sustentabilidad del entorno construido, abarcando las líneas de diseño arquitectónico y urbano sustentable; materiales y tecnologías constructivas sustentables; arquitectura para la salud y el bienestar; y métodos y herramientas de análisis. Si bien en un principio la revista se orientó hacia problemáticas específicas de Latinoamérica, hemos visto cómo su alcance se ha ido ampliando a contribuciones de otros países que conforman el Sur Global, lo cual refuerza su prestigio y relevancia internacional.

En el contexto del Sur Global, el entorno construido enfrenta problemas específicos que difieren de aquellos del Norte Global. Las consecuencias del cambio climático son más severas en este contexto, afectando principalmente a la población más vulnerable. Una proporción importante de la población habita en asentamientos informales, donde la mala calidad de la construcción genera importantes riesgos frente a incendios, inundaciones y olas de calor.
Este número se compone de contribuciones de autores provenientes de Irán, Turquía, Perú, Colombia, Argentina y Chile. Cubre una gran diversidad de temas, desde confort en arquitectura vernácula hasta el desarrollo de nuevos materiales con criterios de sustentabilidad. Agradecemos a todos quienes han confiado en la revista y esperamos que los lectores disfruten su lectura.

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EDITORIAL

I am pleased to introduce this issue of Hábitat Sustentable by sharing the great news of the journal's progress to the Q2 quartile in the Scimago Ranking in the Architecture area. The journal is now ranked 64th among 179 journals in the area, mainly because of the number of citations each article receives, among other criteria based on coverage and impact. Considering just the journals indexed in Scopus for Latin America, HS is second in Architecture and Construction. This achievement is thanks to the hard work of the editorial management team, headed by Jocelyn Vidal, as well as the researchers in the editorial committee and peer review group.

One of HS's main merits is its membership in the "diamond open access" group of journals. This means its articles are published at no cost to authors and readers. At a time when most scientific publications are concentrated in large international for-profit publishing houses, it is motivating for the academic community to have a journal with the characteristics of HS. This is possible thanks to the commitment that the Universidad del Bío-Bío (Chile), through the Faculty of Architecture, Construction and Design and the Vice-Rector's Office for Research and Postgraduate Studies, has had to promote open access to research results.

In 2023, to increase the articles' visibility, we created audiovisual capsules that summarize each published article. These capsules are disseminated on the journal's social networks, such as Instagram and LinkedIn. In this way, the results of academic research can reach not only the academic sphere but also the general public.

Among the future challenges, we feel it is essential to attract authors generating advanced knowledge in built environment sustainability issues, covering sustainable architectural and urban design, sustainable construction materials and technologies, architecture for health and well-being, and analysis methods and tools. Although the journal was initially oriented toward specific problems of Latin America, its scope has been expanding to include contributions from other countries that make up the Global South, which reinforces its prestige and international relevance.

In the context of the Global South, the built environment faces specific problems that differ from those of the Global North. The consequences of climate change are more severe in this context, mainly affecting the most vulnerable population. A significant proportion of the population lives in informal settlements, where the poor quality of construction generates significant risks from fires, floods, and heat waves.

This issue features contributions from authors in Iran, Türkiye, Peru, Colombia, Argentina, and Chile. It covers a wide variety of topics, from comfort in vernacular architecture to the development of new materials with sustainability criteria. We thank everyone who has trusted the journal and hope readers enjoy reading it.

Editorial
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EDITORIAL

É com grande satisfação que apresento este número da revista Habitat Sustentável, compartilhando a boa notícia do avanço da revista para o quartil Q2 no ranking Scimago, área de Arquitetura. Com isso, a revista passa a ocupar a posição de número 64 entre 179 periódicos da área, principalmente em função do número de citações recebidas por cada um de seus artigos, entre outros critérios de abrangência e impacto. Se considerarmos apenas as revistas indexadas na Scopus na América Latina, a HS está em segundo lugar, tanto na área de Arquitetura quanto na de Construção. Essa conquista se deve ao trabalho árduo da equipe de gestão editorial liderada por Jocelyn Vidal, bem como dos pesquisadores que compõem o comitê editorial e o grupo de revisores.

Um dos principais méritos da HS é pertencer ao grupo de periódicos de "acesso aberto diamante", o que significa que seus artigos são publicados gratuitamente para autores e leitores. Em tempos em que a maioria das publicações científicas está concentrada em grandes editoras internacionais com fins lucrativos, é motivador para a comunidade acadêmica ter uma revista com as características da HS. Isso é possível graças ao compromisso que a Universidad del Bío-Bío (Chile), por meio da Faculdade de Arquitetura, Construção e Design e da Vice-Reitoria de Pesquisa e Pós-Graduação, assumiu para promover o acesso aberto aos resultados de pesquisa.

Durante 2023, para aumentar a visibilidade dos artigos, criamos cápsulas audiovisuais que resumem cada artigo publicado e que são divulgadas nas redes sociais da revista, como Instagram e LinkedIn. Dessa forma, os resultados das pesquisas acadêmicas podem chegar não apenas ao meio acadêmico, mas também ao público em geral.

Como parte dos desafios futuros, acreditamos que é importante atrair autores que estejam gerando conhecimento avançado sobre questões de sustentabilidade no ambiente construído, abrangendo as áreas de projeto arquitetônico e urbano sustentável; materiais e tecnologias de construção sustentáveis; arquitetura para saúde e bem-estar; e métodos e ferramentas de análise. Embora a revista tenha sido inicialmente orientada para questões específicas da América Latina, temos visto como seu escopo tem se expandido para incluir contribuições de outros países que compõem o Sul Global, o que reforça seu prestígio e relevância internacional.

No contexto do Sul Global, o ambiente construído enfrenta problemas específicos que diferem daqueles do Norte Global. As consequências das mudanças climáticas são mais graves nesse contexto, afetando principalmente a população mais vulnerável. Uma proporção significativa da população vive em assentamentos informais, onde a má qualidade da construção gera riscos significativos de incêndios, inundações e ondas de calor.

Esta edição é composta por contribuições de autores do Irã, Turquia, Peru, Colômbia, Argentina e Chile. Ela abrange uma ampla gama de tópicos, desde o conforto na arquitetura vernacular até o desenvolvimento de novos materiais com critérios de sustentabilidade. Agradecemos a todos aqueles que depositaram sua confiança na revista e esperamos que os leitores gostem de lê-la.

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Maureen Trebilcock-Kelly
Coeditora Hábitat Sustentable
Departamento Diseño y Teoría de la Arquitectura, Facultad de Arquitectura, Construcción y Diseño
Universidad del Bío-Bío, Concepción, Chile
https://orcid.org/0000-0002-1984-0259
mtrebilc@ubiobio.cl

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METHODOLOGICAL PROPOSAL FOR MEASURING GLARE IN INDOOR ENVIRONMENTS USING FOUR EYE OPENNESS RANGES

PROPUESTA METODOLÓGICA PARA MEDIR EL DESLUMBRAMIENTO EN AMBIENTES INTERIORES MEDIANTE CUATRO RANGOS DE APERTURA OCULAR

PROPOSTA METODOLÓGICA PARA MEDIR O ENCANDEAMENTO EM AMBIENTES INTERNOS UTILIZANDO QUATRO GAMAS DE ABERTURA OCULA

Julieta Yamin-Garreton
Doctora en Medio Ambiente Visual e Iluminación eficiente
Investigadora del Instituto de Ambiente, Hábitat y Energía (INAHE)
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Mendoza, Argentina
https://orcid.org/0000-0001-9322-2902
jyamin@mendoza-conicet.gob.ar (Autora de Correspondencia)

Darío Jaime
Licenciado en Energías Renovables
Personal de Apoyo - Programador
Instituto de Ambiente, Hábitat y Energía (INAHE), Mendoza, Argentina
https://orcid.org/0009-0008-5617-8736
djaime@mendoza-conicet.gob.ar

Maureen De Gastines
Doctora en Ingeniería
Investigadora del Instituto de Ambiente, Hábitat y Energía (INAHE)
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Mendoza, Argentina
https://orcid.org/0000-0002-0357-9375
mdegastines@mendoza-conicet.gob.ar

Emanuel Schumacher
Ingeniero en Electrónica
Personal de Apoyo del Instituto de Ambiente, Hábitat y Energía (INAHE)
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Mendoza, Argentina
https://orcid.org/0009-0002-4428-2022
eschumacher@mendoza-conicet.gob.ar

Andrea Pattini
Doctora en Medio Ambiente Visual e Iluminación eficiente
Investigadora – Directora del Instituto de Ambiente, Hábitat y Energía (INAHE)
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Mendoza, Argentina
https://orcid.org/0000-0001-6305-1268
apattini@mendoza-conicet.gob.ar

RESUMEN

El desarrollo de modelos de deslumbramiento contribuye a una mejor evaluación del confort visual de los ocupantes en espacios interiores. Los indicadores oculares pueden ser una herramienta adecuada para evaluar el deslumbramiento de manera dinámica en climas soleados para evitar las molestias visuales. En este trabajo, se mide el grado de apertura ocular y se propone su medición en cuatro rangos (oclusión, semi-oclusión, semi-apertura y apertura) por medio de un eye-tracker. El objetivo de este trabajo fue evaluar de qué manera se relaciona el grado de apertura ocular con los niveles de iluminancia vertical (Ev) inferiores a 2484 lx (valor donde aparece la sensación de deslumbramiento molesto), así como determinar si la percepción subjetiva del deslumbramiento de las personas corresponde a los rangos de deslumbramientos propuestos por Wienold (2019). Estos parámetros se midieron en tres condiciones de deslumbramiento percibido (notable, perturbador e intolerable). Los resultados mostraron que la medición de apertura ocular en cuatro rangos, tiene el potencial de cuantificar de manera objetiva y dinámica la sensación de deslumbramiento en todos los escenarios evaluados y en cuanto a su relación con los valores de Ev de referencia, los valores percibidos como notable y perturbador, fueron inferiores a los valores de referencia, mientras que los valores percibidos como intolerable fueron coincidentes.

Palabras clave
deslumbramiento, confort visual, indicadores oculares

ABSTRACT

The development of glare models contributes to a better assessment of occupant's visual comfort in indoor spaces. Eye indicators can dynamically assess glare in sunny climates to avoid visual discomfort. In this work, an eye tracker measures the degree of eye openness in four ranges (occlusion, semi-occlusion, semi-openness, and openness). This work aimed to evaluate how the degree of eye openness is related to vertical illuminance levels (Ev) below 2484 lx (value where the sensation of bothersome glare appears), as well as to determine whether people's subjective perception of glare follows the glare ranges proposed by Wienold (2019). These parameters were measured in three conditions of perceived glare (noticeable, disturbing, and intolerable). The results showed that the measurement of eye openness in four ranges has the potential to objectively and dynamically quantify the sensation of glare in all the scenarios evaluated. Regarding its relationship with the reference Ev values, the values perceived as noticeable and disturbing were lower than the reference values, while the values perceived as intolerable coincided.

Keywords
glare, visual comfort, eye indicators

RESUMO

O desenvolvimento de modelos de ofuscamento contribui para uma melhor avaliação do conforto visual dos ocupantes de ambientes internos. Os indicadores oculares podem ser uma ferramenta adequada para avaliar o ofuscamento de forma dinâmica em climas ensolarados para evitar o desconforto visual. Neste trabalho, o grau de abertura ocular é medido e proposto para ser medido em quatro faixas (oclusão, semi-oclusão, semi-abertura e abertura) por meio de um rastreador ocular. O objetivo deste trabalho foi avaliar como o grau de abertura ocular está relacionado aos níveis de iluminância vertical (Ev) abaixo de 2484 lx (valor em que aparece a sensação de brilho incômodo), bem como determinar se a percepção subjetiva de brilho das pessoas corresponde às faixas de brilho propostas por Wienold (2019). Esses parâmetros foram medidos em três condições de percepção de ofuscamento (perceptível, incômodo e intolerável). Os resultados mostraram que a medição da abertura ocular em quatro faixas tem o potencial de quantificar de forma objetiva e dinâmica a sensação de ofuscamento em todos os cenários avaliados e, em termos de sua relação com os valores de Ev de referência, os valores percebidos como perceptíveis e incômodos foram inferiores aos valores de referência, enquanto os valores percebidos como intoleráveis foram coincidentes.

Palavras-chave:
ofuscamento, conforto visual, indicadores oculares

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INTRODUCTION

It is vital to approach daylighting performance in buildings from two perspectives: energy efficiency and the human factor. Regarding the human factor, a pleasant outdoor view and controlled access to daylight are crucial factors for people's visual comfort (Aries et al., 2010). However, these benefits can be obtained only if the window is accompanied by a suitable solar control element to regulate the level of glare. Glare represents one of the most significant challenges in the search for optimal visual comfort and is a fundamental barrier to the efficient use of daylight in buildings (Shin et al., 2012).

Glare is a sensation produced by luminance within the visual field above the luminance to which the visual system is adapted (DiLaura, 2010). Questionnaires can measure subjective glare experienced by people, where Osterhaus and Bailey's four-point scale is one of the most widely used options. Its denomination uses the terms imperceptible, noticeable, disturbing, and intolerable. On the other hand, some glare models describe the subjective magnitude of glare experienced by observers (CIE, 2020). These models consist of photometric measurements adjusted to people's responses, obtained, for example, from the previously mentioned Osterhaus and Bailey 4-point scale. A peculiarity of these models is that they consider the gaze's direction at a fixed point (Hopkinson, 1950). This is a significant limitation of the models since the direction of the gaze is dynamic and forces the eye to readapt to the different photometric conditions of the environment (Kokoschka & Haubner, 1985). Therefore, it is challenging to evaluate the occupants' effective visual comfort from fixed measurements in a workplace (Johra et al., 2021).

The most widely used models are the DGP (Wienold & Christoffersen, 2006) and the Ev metric (vertical illuminance at eye level) (Wienold et al., 2019). However, the applicability of the DGP and Ev metrics is limited by the dataset's scope, as they cannot represent the entire spectrum of lighting scenarios encountered in real-world situations (Quek et al., 2021). There are also many psychological aspects, such as emotional state, level of sensitivity to glare, interpretation of questionnaires and scales, and physiological ones, such as visual correction, ocular pigmentation, and chronotype, that could influence glare sensation and have not yet been well identified. Many of them are described in detail in the literature review article by Pierson et al. (2017).

A recent literature review of people's physiological response to visual discomfort conditions in office spaces showed many things that needed more consistency in the existing models. It also highlighted the need for a more objective method to derive glare indices, such as people's physiological responses (Hamedani et al., 2019). The physiological response recorded using an eye tracker can contribute to a dynamic evaluation of the gaze, considering the setting's light fluctuations (Sarey Khanie, 2015).

The nature of these physiological responses is found in the human body's autonomic nervous system, which, through different reflexes, tries to reduce the fluctuations of the surroundings, such as excess light, and keep the body physiologically stable (Boyce, 2003). Some of the visual adaptation mechanisms have been extensively studied, but those that still require further statistical validation are:

- Degree of eye opening: A first study showed that excess light in the eye area produced changes in the activities of the facial muscles around the eye (Berman et al., 1993). Subsequently, this indicator showed a high correlation with the glare perceived by people under disturbing and intolerable glare (Yamin Garretón et al., 2015; Yamin Garretón et al., 2016).
- Frequency and amplitude of spontaneous eye blinking: Spontaneous blinking can be affected by a source of glare, especially if subjects look slightly upwards (Doughty, 2014). On the other hand, other studies have shown an increase in blinking frequency in office work with the use of VDU (Visual Display Units) (Yamin Garretón et al., 2016).
- Relative pupil size: This indicator showed a medium and significant correlation with the subjective evaluation of people against glare (Lin et al., 2015) and is considered the best predictor of "disturbing and intolerable" glare (Hamedani et al., 2020b).
- Eye movements: Several studies have shown a significant correlation between the feeling of glare and people's responses (Hamedani et al., 2020a; Lin et al., 2015; Sarey Khanie et al., 2013; Yamin Garretón et al., 2016).

These eye indicators initially proved an adequate tool for evaluating glare in sunny climates. However, additional studies are required to validate their use and extend their application since they were studied in glare situations from 3000 lx to 11000 lx of vertical illuminance at eye level (Yamin Garretón et al., 2015). These indicators have not yet been tested in situations of lower vertical illuminance, frequently found in office spaces. A significant value to detect is the threshold value between imperceptible and

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Table 1. Three ranges of glare. Source: Preparation by the authors.

Metric	Threshold values ('cut-off')		
	Imperceptible-noticeable BIN	Noticeable-Disturbing BNP	Disturbing-Intolerable BPI
Ev	2484 lx	3359 lx	4384 lx

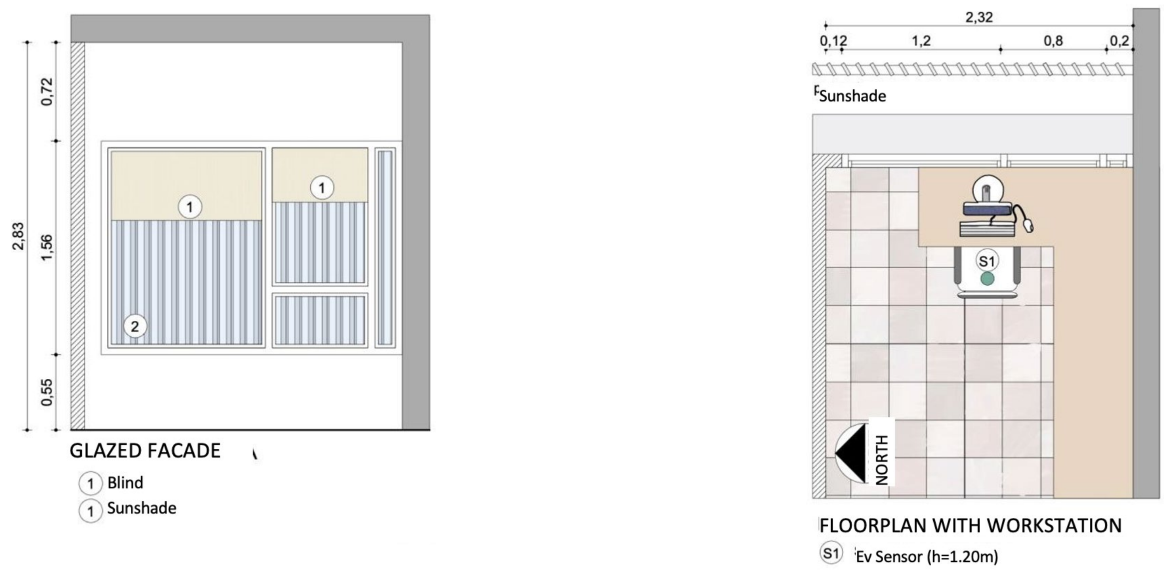

Figure 1. On the glazed facade (top), the two types of control elements used and the window's dimensions are observed. On the ground floor, the workstation and the location of the vertical illuminance sensor are seen. Source: Preparation by the authors.

noticeable glare of 2484 lx established by Wienold et al. (2019). This threshold value determines the boundary between visual comfort and discomfort. This value, also called BCD (borderline comfort discomfort), has its origin in the experiments of Luckiesh and Guth (1949).

The following work proposes using eye opening from an objective and dynamic perspective to quantify the glare using a novel methodology. This indicator will be measured using four opening ranges (occlusion, semi-occlusion, semi-opening, and opening). The objective of validating these eye indicators is to:

- Determine how the degree of eye opening is related to vertical illuminance levels below 2484 lx (the value where discomfort due to glare appears) and whether people's subjective perception of glare follows the Ev ranges proposed by Wienold et al. (2019).
- A more accurate assessment of glare, which considers the dynamism of vision and detects the occurrence of uncomfortable glare in indoor spaces such as offices, can prevent people from blocking windows due to the potential risk of glare. A window with access to controlled daylighting and without glare sources provides the benefits of an outside view, improving cognitive function (Sharam et al., 2023) and the operation of the circadian system (Mathew et al., 2023), among other vital aspects mentioned in Abd-Alhamid et al. (2023).

METHODOLOGY

The research uses an eye tracker to measure eye behavior through eye opening in four ranges (occlusion/semi-occlusion/semi-opening, and opening). These parameters were measured in three lighting conditions: NG (noticeable glare), DG (disturbing glare), and IG (intolerable glare), considering the subjective sensation of glare. The participants defined these by the time they could tolerate each situation with glare (Osterhaus, 1996;

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Figure 2. The six figures show an example of the three glare conditions generated by users when adjusting the roller blinds and monitor position on the desk. Only the right blind was adjusted. A photo was taken with a fisheye lens with a viewing angle of 180° to have a complete view of the surroundings. Source: Preparation by the authors.

Introduction 8′		Exposure 1 11′	R 20′	Exposure 2 11′	R 20′	Exposure 3 11′	
-Explanation of the experiment - Signature of informed consent - Placement of the eye-tracker	Participant	Adjustment of lighting conditions 3′ Reading task 5′ Completion of questionnaire 3′		Same as exposure 1		Same as exposure 1	End
	Evaluator	Monitoring of vertical illuminance reaching the eye					

Exposure sequence adjusted randomly

Figure 3. The sequence of activities in the experiment. R (rest time). Source: Preparation by the authors.

Osterhaus & Bailey, 1992). The detailed description can be found in the section: Adjustment of lighting conditions.

Nine participants were evaluated in these three lighting conditions. Each had to perform a reading task in an office at the CCT-Conicet Scientific and Technological Center, Mendoza. The measurements were made from approximately 9:00 to 10:00 a.m. on the spring equinox in September (start time: solar altitude 13.06° and azimuth 108) and October (start time: solar altitude 22°, azimuth 100) 2023. The measurements were made on sunny days. The artificial lighting was turned off during the experiment, and only daylighting from the window was used. The windows are facing east and are 2.00 x 1.56 m in size, with indoor roller shades and outdoor vertical sunshades (Figure 1). The workstation's layout allowed a front, perpendicular, and/or parallel view of the window (Figure 2). The experimental procedure is detailed in depth in the section - Experimental Sequence.

The vertical illuminance reaching the eye (ev) was monitored. This indicator is suitable only when the amount of light reaching the eyes is high and exceeds the effect produced by the contrast between the source's luminance and the background (Wienold et al., 2019), as in this experiment. The objective was to identify how the degree of eye opening is related to vertical illuminance levels below 2484 lx, as well as to determine whether people's subjective perception of glare coincides with the ranges of glare proposed by Wienold et al. (2019) indicated in Table 1.

To participate in the experiment, the nine study participants (7 women and 2 men) had to have specific characteristics, such as normal vision and good health. The ages of the participants were: mean=35, SD=6.39, min=23, max=40. This sample incorporates nine people selected as experimental subjects from a previous study with a larger sample size (Yamin Garretón et al., 2015). Based on epidemiological statistical tests of specificity and sensitivity, the participants were classified as experienced subjects and selected for the trial. Sensitivity is the probability that the person identifies glare as a condition that it effectively is, and specificity is the probability that the person

Table 2. Glare scale used. Source: Preparation by the authors.

Name	Question	Answer
Binary	Are you experiencing any discomfort due to glare at the moment?	Yes No
Osterhaus-Bailey Scale	At this point, how would you describe the level of glare in your field of vision?	Imperceptible Noticeable Disturbing Intolerable

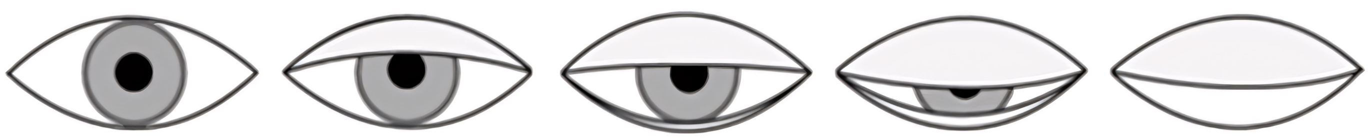

Figure 4. Different percentages of eye opening. Source: Preparation by the authors.

identifies as non-glare, a light condition that is not as such. The relationship between sensitivity and specificity provides diagnostic accuracy. The stepwise calculation of this methodology can be found in Rodriguez et al. (2017). This methodology of working with a small but experienced group has been validated in some glare works (Hopkinson, 1957; Suk et al., 2016).

EXPERIMENTAL SEQUENCE

The sequence of activities performed by the participants and evaluators during the experiment can be seen in Figure 3.

Adjustment of lighting conditions: As shown in Figure 3, the participants (A) had to accommodate their workplace by using the roller blinds, raising or lowering them, and positioning the screen to generate different directions of vision concerning the window. 0° (direct to the window), 90° (parallel to the window), and 45° (perpendicular to the window) view.

By modifying their workspace, the participants were able to experience the three lighting conditions: noticeable, disturbing, and intolerable. Previously, they were provided with a definition of the three conditions based on the time in which they could tolerate each glare situation (Osterhaus, 1996; Osterhaus & Bailey, 1992).

1. Noticeable Glare: This is the point where the glare is noticed for the first time, or there is a slight experience of discomfort, but it can be tolerated for several hours.

Table 3. Opening ranges. Source: Preparation by the authors.

Percentage of opening	Reference name
0-25%	Occlusion
25-50%	Semi-occlusion
50-75%	Semi-opening
75-100%	Opening

2. Disturbing glare: This was defined as an experience of discomfort where glare can be tolerated for 15 to 30 minutes and requires a change of lighting conditions.
3. Intolerable Glare: The subjects cannot stand the glare; they have a tipping point requiring immediate lighting changes.

Reading task: As shown in Figure 3 below, the participants (B) performed a reading task with their eyes fixed on the screen. The text was projected on its upper margin, and the person had to scroll it with the mouse. However, not their vision since directing the vision downwards implies that the eyelids close, lubricating the eye and reducing the appearance of blinking. This task was performed to obtain a cleaner signal with the vision as fixed as possible on the screen. People read the text on the screen in 5 minutes, enough time for the eye to adapt to the specific light conditions.

Filling out the questionnaire: At the end of the task, as shown in Figure 3, the participants (C) filled out a

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questionnaire for each of the three exposures (Table 2). The order of the exposures was randomized to avoid order bias. The resting time between each exposure was 20 minutes, necessary for the participants' eyes to readjust and prepare for the following exposure.

Vertical illuminance monitoring: As seen in Figure 3, the evaluators (D) monitored and recorded the vertical illuminance at eye level at the beginning and end of the reading task performed by the participants; to corroborate that, the vertical illuminance value did not vary significantly during the completion of the task. Scenarios in which the illuminance value did not differ significantly between the first and second measurements were considered valid. The average value of the two recorded points was reported. The illuminance sensor consisted of an "LMT Lux 2 lux meter," measuring from 0.1 to 200000 lx, and a calibration date in 2023. This sensor was mounted on a tripod and located at the participant's eye level in the direction of the task at a 45° angle.

EYE REGISTRATION

The degree of muscle contraction around the eyes that reduces the incoming light was measured based on the Tsao model (Tsao, 2008) defined by equation (1):

$$DEO = L/L_{max} \quad (1)$$

Where DEO is the eye opening percentage, L is the eye opening level in the presence of a source of glare, and L max is the maximum height of the eye when it is fully open. A threshold value was established to define whether the eye was open or closed: if the ratio was less than 0.2, the eye was considered closed. Otherwise, it was defined as open (Figure 4).

This work proposes classifying the eye openings into four equally distributed ranges (Table 3) to calculate the time when the eyes were in said opening.

DESCRIPTION OF THE EYE-TRACKER

The eye tracker was explicitly designed for this study (Figure 5). It consists of a helmet on which a high-quality webcam (720p quality, 1/4" lens size, lens viewing angle: 68.6°) is mounted using an articulated arm that records the image of the participants' faces. The images are taken at 30 frames per second, showing a fixed portion of the face.

The analysis of the recorded images consisted first of performing facial recognition of the individuals using the MediaPipe Face Landmark Detection model

Figure 5. Eye-tracker in use. Source: Preparation by the authors.

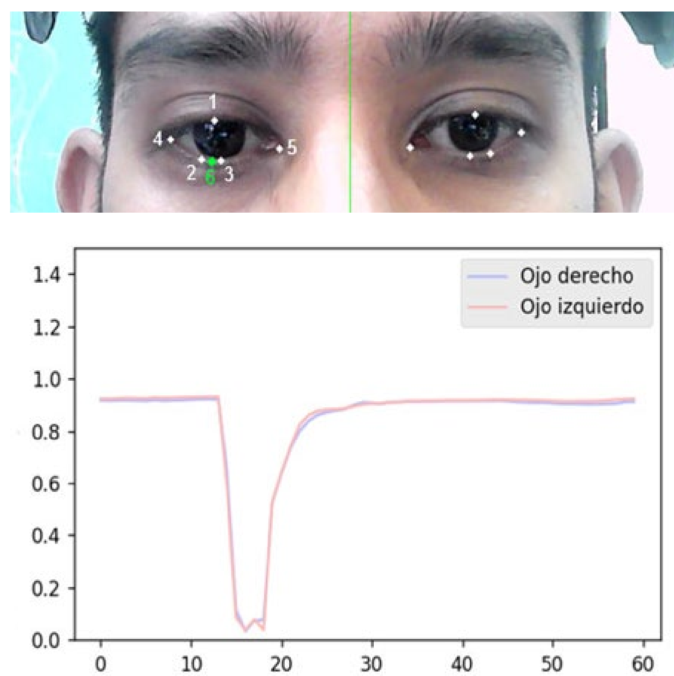

Figure 6. Camera and script in operation. Left: video capturing the 10 points of interest detected in white. Right: Eye opening reading of the last 60 frames. Source: Preparation by the authors.

Table 4. Vertical illuminance (Ev) measurements recorded in the three scenarios evaluated. Source: Preparation by the authors.

Ev	NG	DG	IG
Min	1050 lx	1100 lx	3600 lx
Max	2000 lx	3800 lx	12000 lx
Average	1496.11 lx	2411.11 lx	6966.66 lx
SD	353.07 lx	706.12 lx	2723.96 lx

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Table 5. Eye aperture values (mean, median, and SD) for the sensation of noticeable glare (NG). Source: Preparation by the authors.

NG	Opening 0-1		
	mean	median	SD
Participant 1	0.92	0.94	0.08
Participant 2	0.83	0.86	0.12
Participant 3	0.86	0.91	0.16
Participante4	0.71	0.76	0.18
Participant 5	0.87	0.88	0.08
Participant 6	0.80	0.84	0.15
Participant 7	0.78	0.80	0.10
Participant 8	0.79	0.80	0.08
Participant 9	0.84	0.84	0.11
Median total	0.82	0.85	0.12
SD total	0.06	0.06	0.04

Table 6. Eye opening values (mean, median, and SD) for the sensation of disturbing glare (DG). Source: Preparation by the authors.

DG	Opening 0-1		
	mean	median	SD
Participant 1	0.85	0.86	0.11
Participant 2	0.80	0.82	0.10
Participant 3	0.75	0.79	0.13
Participante4	0.75	0.81	0.18
Participant 5	0.89	0.90	0.07
Participant 6	0.72	0.75	0.14
Participant 7	0.81	0.82	0.09
Participant 8	0.89	0.90	0.07
Participant 9	0.78	0.79	0.09
Median total	0.80	0.82	0.10
SD total	0.06	0.05	0.04

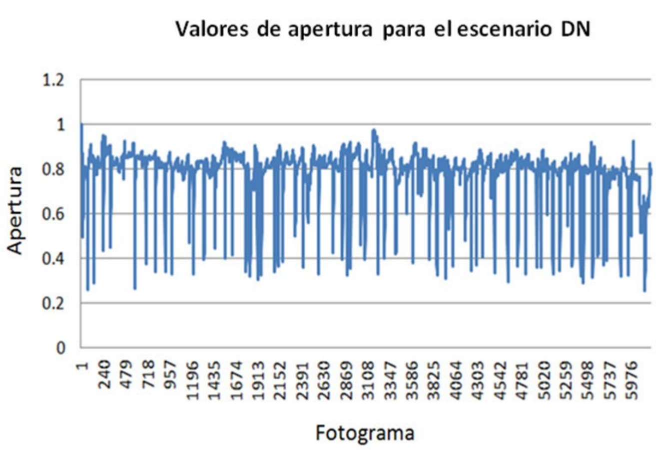

Figure 7. Participant 2's eye opening values for the NG scenario over time (30 frames per second). Source: Preparation by the authors.

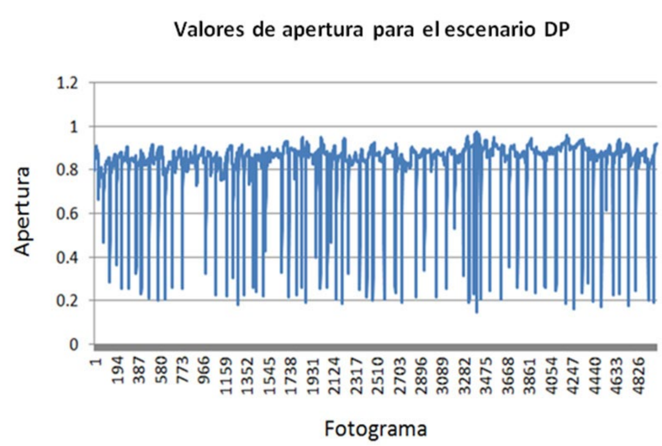

Figure 8. Participant 2's eye opening values for the DG scenario over time (30 frames per second). Source: Preparation by the authors.

(Bazarevsky et al., 2019; Yan & Grishchenko, 2022) using 478 facial points, of which only ten were of interest, those for the eyes. Then, through a script written in Python, the coordinates of the points of interest were calculated. The eye opening was calculated from the distance between two fundamental points, point 1 for the upper eyelid and point 6 for the lower eyelid, which is the average distance between points 2 and 3 (Figure 6. Left).

RESULTS AND DISCUSSION

Table 4 shows Ev's minimum, maximum, mean, and standard deviation (Sd) values recorded under the three conditions.

Table 4 shows the Ev measurements recorded during the visual task performance, which refer to the perceived glare. The average Ev values show that in the scenarios with glare perceived as noticeable and disturbing, the Ev values were lower than the reference values of Table 1. However, the glare values perceived as intolerable coincided with the reference values of Table 1.

On the other hand, the level of coincidence of the people's answers with the reference values was calculated. It was observed that, for the NG scenario, only 2 of the 9 responses coincided with the reference values proposed by Wienold (2019); for the DG scenario, 3 of the 9 responses coincided with the reference values. For the IG scenario, 9 of the 9 responses coincided with the reference values.

From the average Ev values and the level of coincidence of the subjective responses with the values of Table 1, it can be determined that, in the scenarios of glare perceived as noticeable and disturbing, the Ev values did not coincide with the reference values of Table 1. These differences may be due to other factors besides Ev, such as the presence of unwanted glare or reflections, which may have affected the sensation of glare and were not evaluated in this research.

OPENING VALUES

Tables 5, 6, and 7 show the eye opening values (mean, median, and standard deviation "SD") of the nine participants in the three lighting conditions. At the end of each table, you can also see the total mean (mean_tot) and the total standard deviation (SD_tot) to obtain an opening value per scenario. The frequency of openings in Participant 2's three conditions is shown on the right of each table (Figure 7, Figure 8, and Figure 9).

From the analysis of the total mean and the total SD of the opening values of the three scenarios, it was observed that the opening value was slightly higher (m=0.82) in the NG scenario with lower light levels than in the other two scenarios. This value coincides with the opening range (0.75-1). In the DG scenario with intermediate glare values, the average opening value was slightly lower (0.80) but coincided with a total opening range, so the differences between the NG and DG scenarios are not obvious. Finally, in the IG scenario, the opening value was lower (m=0.73), coinciding with a semi-opening range (0.5-0.75). In this scenario, with higher glare levels, the reduction of the eye opening is evidenced.

Although these data show a general trend that the opening values decrease with increasing light levels, that is, the higher the level of glare, the lower the opening level, this trend is only found in some participants. For example, Participant 8 had a higher average eye opening in the DG scenario (0.89) than in the NG scenario (0.79). In the case of Participant 6, a higher average eye opening value was recorded in the IG scenario (0.82) than in the other two scenarios (0.80 and 0.72).

In the NG (Table 5, participant 4) and DG (Table 6, participant 6) scenarios, lower opening values (eye in semi-opening) are also observed compared to the rest of the participants (eye in opening). This shows

Table 7. Eye opening values (mean, median, and SD) for the Intolerable glare (IG) sensation.Source: Preparation by the authors.

IG	opening 0-1		
	mean	median	SD
Participant 1	0.75	0.76	0.07
Participant 2	0.72	0.74	0.09
Participant 3	0.60	0.60	0.09
Participante4	0.69	0.74	0.16
Participant 5	0.73	0.73	0.08
Participant 6	0.82	0.86	0.14
Participant 7	0.78	0.78	0.08
Participant 8	0.72	0.73	0.11
Participant 9	0.75	0.75	0.11
Median total	0.73	0.75	0.11
SD total	0.06	0.07	0.03

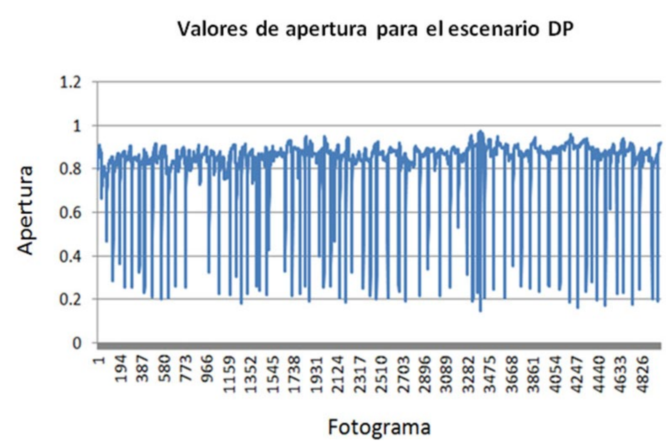

Figure 9. Participant 2's eye opening values for the IG scenario over time (30 frames per second). Source: Preparation by the authors.

Table 8. Wilcoxon Z-tests for comparison of means (non-parametric tests). Source: Preparation by the authors.

	Z-Wilcoxon	Sig. (bilateral)
NG-DG	-0.830	0.407
NG-IG	-2.313	0.021
DG-IG	-2.018	0.044

Table 9. Percentage of time in the 4 opening ranges for the three conditions of perceived glare. The total time for each situation was 100%. Source: Preparation by the authors.

	NG				DG				IG			
	0-0.25	0.25-0.50	0.50-0.75	0.75-1	0-0.25	0.25-0.50	0.50-0.75	0.75-1	0-0.25	0.25-0.50	0.50-0.75	0.75-1
P1	1.8%	2.7%	5.1%	90.4%	1.5%	2.8%	12.4%	83.3%	1.1%	4.0%	38.0%	54.1%
P 2	1.6%	1.9%	3.7%	92.8%	0.2%	2.7%	15.1%	81.9%	0.6%	4.0%	49.8%	45.6%
P 3	1.2%	4.8%	4.4%	89.7%	1.1%	4.4%	17.0%	77.5%	0.0%	13.7%	78.8%	7.5%
P 4	5.0%	4.1%	5.6%	85.2%	5.1%	5.5%	16.8%	72.5%	5.6%	5.0%	39.0%	50.5%
P 5	0.8%	0.4%	1.2%	97.6%	0.2%	0.4%	7.7%	91.7%	0.2%	1.6%	46.1%	52.0%
P 6	1.8%	2.8%	6.7%	88.7%	1.6%	3.4%	14.2%	80.9%	1.6%	4.0%	7.1%	87.3%
P 7	1.2%	0.8%	2.8%	95.3%	0.8%	0.8%	1.4%	97.0%	0.4%	1.4%	12.5%	85.7%
P 8	1.0%	1.0%	6.2%	91.9%	0.2%	0.8%	17.2%	81.8%	0.8%	2.9%	44.3%	52.0%
P 9	1.0%	2.9%	5.3%	90.9%	1.8%	1.8%	14.0%	82.4%	1.0%	4.0%	41.3%	53.8%
Me	1.7%	2.4%	4.5%	91.4%	1.4%	2.5%	12.9%	83.2%	1.2%	4.5%	39.7%	54.3%
	100%				100%				100%			
De	1.3	1.4	1.7	3.6	1.5	1.7	5.2	7.2	1.6	3.6	20.9	23.3

Table 10. Wilcoxon tests for comparison of means, bilateral p-significance. Source: Preparation by the authors.

	Occlusion		Semi-occlusion		Semi-opening		Opening	
	Z	p	Z	p	Z	p	Z	p
NG - DG	-0,984	0.325	-0.254	0.799	-2.549	0.011	-2.192	0.028
NG - IG	-1,544	0.123	-2.673	0.008	-2.666	0.008	-2.666	0.08
DG - IG	-0,511	0.610	-2.442	0.015	-1.599	0.110	-1.599	0.110

that the average opening values (mean) are not a sufficiently robust statistical test to discriminate the three conditions of perceived glare. Although the IG scenario was statistically different from the other two scenarios ($p<0.05$) (Table 8), the NG scenario was not statistically different from the DG ($p>0.05$) (Table 8). To determine the difference between these two scenarios (NG-DG), the duration of the participants' stay in the 4 opening conditions (occlusion, semi-occlusion, semi-opening, opening) was calculated.

ANALYSIS OF THE FOUR OPENING RANGES

Table 9 shows the percentage of time the participants' eyes were in the 4 opening ranges for the three conditions of perceived glare. In general, it can be said that, in the three conditions of perceived glare, the eyes were open longer (0.75-1), and it was also observed that the opening in this range decreased as the glare increased. More particularly, the following observations can be made regarding the four opening ranges. On the one hand, the mean values of the percentage of time in occlusion (0-0.25) were 1.7% (NG scenario), 1.4% (DG scenario), and 1.2% (IG scenario). The z-Wilcoxon tests (Table 10) show that there were no statistically significant differences (p>0.05) between the three scenarios (Table 9). On the other hand, the mean values of the percentage of time in semi-occlusion (0.25-0.50) were 2.4% (NG scenario), 2.5% (DG scenario), and 4.5% (IG scenario), with significant differences only between the NG and IG scenarios and between DG and IG (p<0.05). Regarding the mean values in the semi-opening range (0.50 - 0.75), it is evident that the time quadruples between the DG scenario (12.9%) and the NG (4.5%) and almost triples between the IG scenario (39%) and the DG (12.9%). Meanwhile, the statistical tests showed significant differences between the NG and DG scenarios and between NG and IG (p<0.05). Finally, in total opening (0.75-1), there were only significant differences between the DG (83.2%) and IG (54.3%) scenarios.

From the previously reported analysis, it is important to emphasize that it is impossible to differentiate the three light scenarios in the total occlusion range. On the contrary, the NG scenario was differentiated from the DG one in the semi-opening and opening ranges. The NG scenario was distinguished from the IG in the semi-opening and semi-occlusion ranges. Finally, the semi-occlusion range was the only one to differentiate the DG scenario from the IG. It is important to highlight that eye indicators could discriminate all the light scenarios evaluated. The three opening ranges that provided the most information were semi-occlusion, semi-opening, and opening.

The percentage of time spent in the different ranges of eye opening defined in the research is a significant indicator of the level of glare since it allows one to differentiate the 3 existing levels (noticeable, disturbing, and intolerable). Considering this, the result is the most relevant of the study.

It is important to highlight the limitations of this work and the proposals for the future:

In future works, the lighting ranges presented to the participants could be considered in two ways: predefined by the evaluators so that all participants experience the same conditions of perceived glare or adjusted by the participants according to their previous experience (as was the case in this experiment).

In future works, vertical illuminance measurements should be complemented by glare models such as the DGP model, which includes luminance contrast measurements. It is also important to evaluate different tasks, not just reading tasks on the screen, as typical office tasks include tasks on a horizontal plane (keyboard, paper).

In addition, it is necessary to include more participants with different levels of glare sensitivity to obtain more robust results. It would also be important to complement the proposed methodology with other eye indicators, such as the number of blinks, or perform frequency analysis to detect patterns in eye behavior that are repeated under different conditions of perceived glare.

In the same way, it would be interesting, in future works, to contrast the information obtained from the questionnaires about visual comfort and relate it to the eye indicators to determine if there are biases in people's responses, a product of the experimental design. Numerous suggestions and criticisms have been made about the validity of the questions used in subjective questionnaires (Fotios & Kent, 2021; Quek et al., 2023). This is related to the appearance of different types of biases in experimental designs, such as the Hawthorne effect, "modification of the participant's response as a result of knowing that they are being studied, and not in response to the experimental study" (Perera, 2023), among other types of bias.

Finally, the research contributes to laying the foundations for creating a control system to regulate the shading devices in offices dynamically, using glare measurements following eye openings in contrast to current light measurements carried out at a fixed measurement point.

CONCLUSIONS

The physical models are adapted to people's answers through questionnaires. However, these questionnaires have limited validity (Quek et al., 2023) and may influence the answers obtained depending on the type of questionnaire used. The eye indicators could provide objective information regarding the degree of glare experienced by the participants to quantify the sensation of people. Another limitation is that the models are placed in a fixed position due to the sensors' location and consider the gaze's direction in a limited direction. On the other hand, eye indicators dynamically provide information about the gaze, registering the different photometric conditions of the environment through ocular fluctuations.

The research aimed to propose four eye opening ranges to evaluate glare. On the analyzed sample, a tendency was found that discrimination of the perceived glare conditions (NG-DG-IG) is possible from three opening ranges: semi-occlusion (0.25-0.50) and semi-opening (0.50-0.75) and opening (0.75-1). While in the occlusion range (0-0.25), it was not possible to differentiate the three light scenarios. The proposed ranges consisted of 4 equally distributed ranges. In future works, the distribution of the ranges could be adjusted to analyze the glare levels more effectively.

Regarding the level of coincidence of people's responses and the values proposed by Wienold et al. (2019), it can be concluded that, based on the average values and the level of coincidence of the subjective responses in the scenarios of perceived glare as noticeable and disturbing, the mean Ev values were lower than the reference values, while the values of perceived glare as intolerable are coincident with the reference values of Table 1. However, more validation studies are needed to confirm these findings.

It is important to note that previous studies to this work (Hamedani et al., 2019) had already found that it was possible to quantify, by eye indicators, the presence of glare in disturbing and intolerable glare. This study visualized the possibility of differentiating between noticeable and disturbing glare conditions. Adjusting the tools, which help develop glare models or increase their validity, could improve the evaluation of the occupants' visual comfort in indoor spaces. In turn, this work aims to lay the foundations for developing an algorithm capable of identifying eye patterns to make automatic adjustments in shading devices.

It is important to note that previous studies to this work (Hamedani et al., 2019) had already found the possibility of quantifying the presence of glare using eye indicators. More specifically, some studies conducted in recent years (Hamedani et al., 2020) showed that blink amplitude and pupillary agitation index could quantify certain relative glare conditions (including imperceptible and noticeable glare conditions), while eye movements (fixations) and pupil diameter could quantify more extreme levels of glare (disturbing and intolerable). The difference in this study, concerning those previously analyzed, is that in this research, the possibility of differentiating the entire spectrum of glare conditions, ranging from noticeable to disturbing and intolerable, was determined using a single eye indicator: the eye opening in its four ranges. Adjusting the tools that help develop glare models or increase their validity can improve the evaluation of the occupants' visual comfort in interior spaces.

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THERMAL PERCEPTION OF USERS IN THE VERNACULAR HOUSING OF THE URO COMMUNITY OF LAKE TITICACA IN PERU

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PERCEPCIÓN TÉRMICA DE USUARIOS EN LA VIVIENDA VERNÁCULA DE LA COMUNIDAD URO DEL LAGO TITICACA EN PERÚ

PERCEPÇÃO TÉRMICA DOS USUÁRIOS NA HABITAÇÃO VERNACULAR DA COMUNIDADE URO DO LAGO TITICACA, NO PERU

Diana Karen Pari-Quispe
Magíster en Arquitectura y Urbanismo
Docente e investigadora Escuela Profesional de Arquitectura y Urbanismo
Universidad Nacional del Altiplano, Puno, Perú
https://orcid.org/0000-0002-1580-2968
diana.pari@unap.edu.pe (Autora de Correspondencia)

Joára Cronemberger-Ribeiro Silva
Doctora Arquitectura y Construcción
Docente y Vice-coordinadora del Laboratorio de Control Ambiental y Eficiencia Energética (LACAM),
Facultad de Arquitectura y Urbanismo Universidade de Brasília, Brasil
https://orcid.org/0000-0002-8649-451X
joaracronemberger@unb.br

Samuel Huaquisto-Cáceres
Doctor Ciencia Tecnología y Medio Ambiente
Docente e Investigador RENACYT, Escuela Profesional de Ingeniería Civil
Universidad Nacional del Altiplano, Puno, Perú
https://orcid.org/0000-0002-9294-6359
shuaquisto@unap.edu.pe

Hugo Anselmo Ccama-Condori
Doctor Ciencia Tecnología y Medio Ambiente
Docente e Investigador, Director del Instituto de Investigación en Arquitectura y Construcciones (IARCO),
Escuela Profesional de Arquitectura y Urbanismo, Universidad Nacional del Altiplano, Puno, Perú
https://orcid.org/0000-0003-2886-7901
hccama@unap.edu.pe

Leyda Cinthia Aza-Medina
Magíster en Tecnología en la Arquitectura
Docente e investigadora RENACYT, Escuela Profesional de Arquitectura y Urbanismo
Universidad Nacional del Altiplano, Puno, Perú
https://orcid.org/0000-0002-3707-2126
lcaza@unap.edu.pe

RESUMEN

El objetivo de la siguiente investigación fue realizar un estudio de campo, para conocer la percepción térmica de los usuarios de la vivienda vernácula en clima frío de la región Altoandina peruana. Las unidades analizadas fueron viviendas construidas en base a "totora" de la comunidad Uro. El estudio de campo desarrollado consistió en caracterizar el desempeño térmico de la vivienda, determinar la superficie corporal y aislamiento de ropa, valorar la sensación, preferencia y aceptabilidad térmica, determinar las estrategias de ajustes personales y calcular la temperatura neutra. Se recogieron 78 encuestas válidas en dos períodos estacionarios (verano e invierno). Los resultados revelan que, los usuarios de la vivienda se encuentran incómodos. La preferencia apunta a ambientes más cálidos y secos. La temperatura neutra en verano fue de 19.62 °C y en invierno de 21.98 °C. Los habitantes del lugar evidenciaron tener la expectativa que el ambiente puede mejorarse térmicamente con mayor aislamiento.

Palabras clave
vivienda vernácula, confort térmico, percepción térmica, condición climática.

ABSTRACT

The objective of this work was to conduct a field study to determine the thermal perception of users of vernacular housing in the cold climate of the Peruvian High Andean region. The units analyzed were houses built by the Uro community using "totora" (bulrush reeds). The field study characterized the dwelling's thermal performance, determined body surface area and clothing insulation, assessed thermal sensation, preference, and acceptability, determined personal adjustment strategies, and calculated the neutral temperature. Seventy-eight valid surveys were collected in two periods (summer and winter). The results reveal that the dwelling's users are uncomfortable. The preference points to warmer and drier environments. The neutral temperature was 19.62 °C in summer and 21.98 °C in winter. However, the inhabitants had the expectation that the environment could be thermally improved with more insulation.

Keywords
vernacular housing, thermal comfort, thermal perception, climate conditions.

RESUMO

O objetivo da pesquisa a seguir foi realizar um estudo de campo para descobrir a percepção térmica dos usuários de habitações vernaculares no clima frio da região dos Altos Andes peruanos. As unidades analisadas foram moradias construídas em "totora" da comunidade Uro. O estudo de campo consistiu em caracterizar o desempenho térmico da habitação, determinar a área de superfície corporal e o isolamento das roupas, avaliar a sensação, preferência e aceitabilidade térmica, determinar as estratégias de ajuste pessoal e calcular a temperatura neutra. Setenta e oito questionários válidos foram coletados em dois períodos sazonais (verão e inverno). Os resultados revelam que os usuários da residência não se sentem confortáveis. A preferência é por ambientes mais quentes e secos. A temperatura neutra no verão foi de 19,62 °C e de 21,98 °C no inverno. Os habitantes do local evidenciaram a expectativa de que o ambiente possa ser melhorado termicamente com mais isolamento.

Palavras-chave:
habitação vernacular, conforto térmico, percepção térmica, condição climática.

INTRODUCTION

The High Andean region of Peru has a cold tundra and glacial climate, high solar radiation, low annual thermal oscillation, and high diurnal thermal oscillation. Due to this climatic variability, the thermal behavior of buildings is different, and the altitude greatly influences it (Molina et al., 2023). In this context, the Uro community faces discomfort, respiratory diseases, and even death during the winter period. To mitigate this situation, the locals usually wear thick clothes to protect themselves from the cold. According to records of the SENAMHI (National Meteorology and Hydrology Service of Peru), the average outdoor temperature in the community drops to 3.50 °C in summer and -1.60 °C in winter, which shows the location's adverse climate.

The Uro community is located on Lake Titicaca, considered the world's highest navigable lake at 3800 meters above sea level. It is an ancient people whose existence dates back to before 500 A.D. Its life is intimately linked to the lake and its resources. Of the total population, 60% are settled on floating islands, and the rest live on dry land. The "Totora" or Southern Bulrush (Schoenoplectus Tatora) is the primary means of subsistence (Aza-Medina et al., 2023, p. 2; Hidalgo-Cordero et al., 2023) whether the material is arranged loosely, braided, or woven like blankets, or in the construction of artificial islands, houses, boats (Hidalgo-Cordero & Aza-Medina, 2023, p. 2; Hýsková et al., 2020).

Significant studies have been carried out on thermal comfort in vernacular dwellings in low-altitude regions (Costa-Carrapiço et al., 2022; Malik & Bardhan, 2022; Widera, 2021). However, few studies were found in high-altitude regions, so it is necessary to investigate, considering that thermal comfort is one of the essential parameters that can provide information for the adaptation of strategies in housing due to its impact on human health, productivity, quality of interior space, and the reduction of energy consumption (Malik & Bardhan, 2022). Providing information to improve housing is crucial and challenging because it depends on many factors that require field studies, such as climatic, psychological, physiological, and cultural aspects (Abdollahzadeh et al., 2023). Therefore, a fundamental issue in conducting field studies is determining the thermal perception of a house's users of temperature changes inside the room (Camuffo, 2019, p. 15).

According to Chang et al. (2021), vernacular housing studies are primarily focused on climate adaptation, which aims to provide climate-adaptive and energy-efficient passive design strategies. Similarly, Xiong et al. (2019) indicate that thermal comfort in vernacular housing focuses on users' adaptability to the climate to provide acceptable thermal environmental conditions. Therefore, vernacular dwellings are places where users adapt to the climate. Hence, improving the internal conditions of the dwelling is required.

In this context, this study aimed to conduct a field study to determine the thermal perception of users of vernacular housing in cold climates typical of the Peruvian High Andean region and provide information on their thermal perception to recommend adaptive strategies to improve their internal conditions.

METHOD

STUDY AREA

The Uro Community

The study area was defined as the Uro community in the department of Puno, Peru, on Lake Titicaca, with a south latitude of 15° 49'14", a west longitude of 69° 58' 12", and an altitude of 3900 meters above sea level. The community is located on floating islands built with "Totora," 5 km from the port city of Puno. The Uros Islands comprise more than 100 units organized in an aligned strip, accessed in the center, and divided into two north and south zones (Figure 1). The islands focused on housing are the most common. These are in a crescent shape with a central space that acts as a yard.

The Uro community's vernacular housing

Its one-floor housing is characterized by its compact shape. The roof is gabled, and the door is used to ventilate the room. The floor is usually boarded with wood or loose reeds and raised 50 cm above the level of the island to prevent moisture entry (Figure 2a). "The structure comprises 2-inch wooden slats recessed with nails" (Steffens et al., 2017, p. 2), which serve as a support (Figure 2b). The house's walls consist of blankets of hand-woven Totora "kesanas," which have an approximate thickness of 3 inches. It was confirmed that the weaving technique of the walls varies compared to that of the roof. In the latter, even longer Totoras were found with a different braiding technique (Figure 2c).

The house has undergone changes with the passage of time. In its beginnings, it had a circular floor plan and a conical roof (Figure 3a). Currently, it has a rectangular or square floor plan (Figure 3b). In addition, modern materials, such as metal sheets, wooden sheets, and plastic, are incorporated into ceilings and walls,

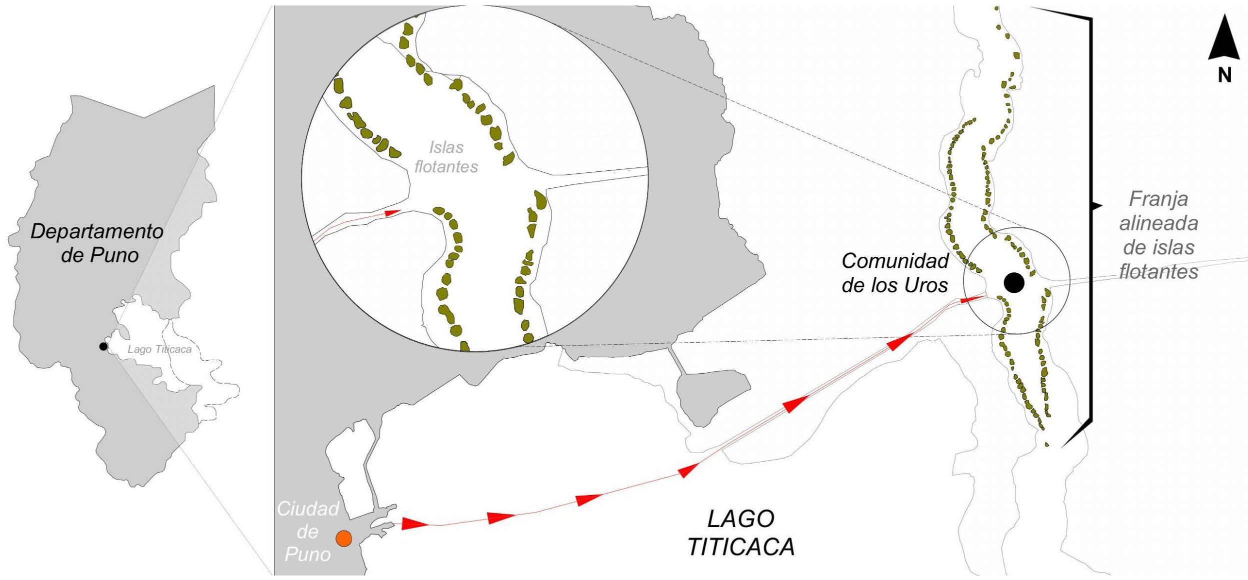

Figure 1. Floating Islands - location. Source: Preparation by the authors.

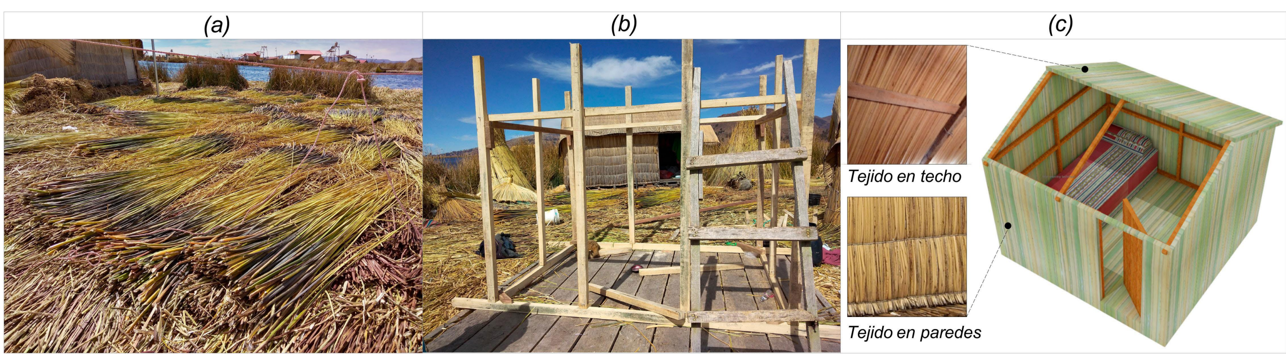

Figure 2. Uro Dwelling - Assembly. Source: Preparation by the authors.

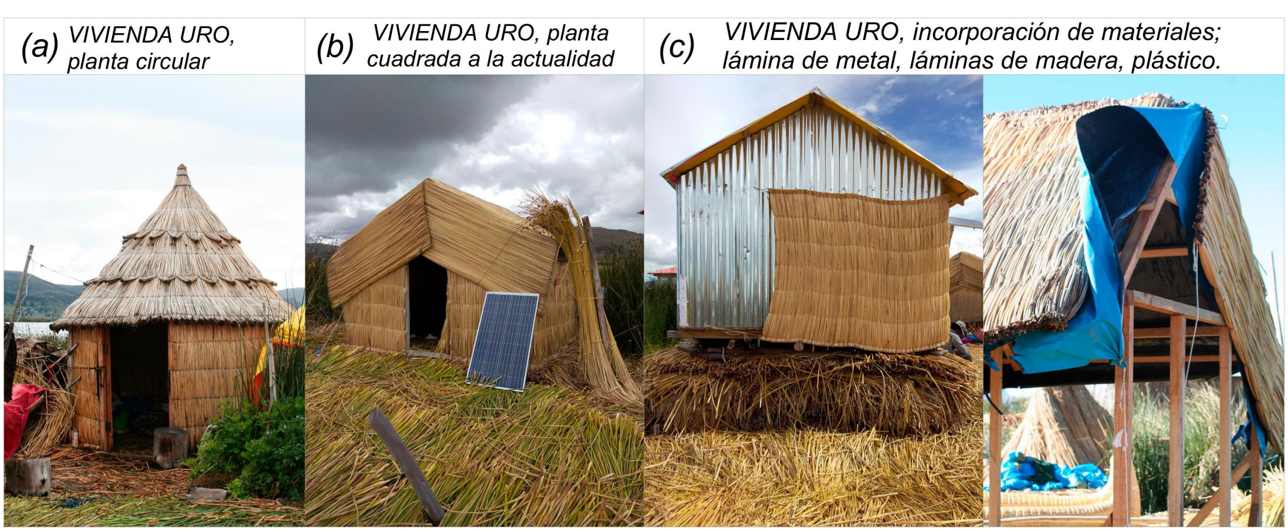

Figure 3. Evolution of shape and materials. Source: Preparation by the authors.

Figure 4. Interior and exterior photos of the vernacular dwellings. Source: Preparation by the authors.

Table 1. Sample size. Source: Preparation by the authors

Description		Total		Summer		Winter	
		n = 78		n = 50		n =28	
		Sample	Percentage	Sample	Percentage	Sample	Percentage
Gender	Female	52	67%	33	66%	19	68%
	Male	26	33%	17	34%	9	32%

disfiguring the indigenous version (Figure 3c).

The internal use of the buildings is mainly as a multi-purpose room, fulfilling the roles of kitchen, storage room, and bedroom, handling the basic needs in one place (Figure 4a) and, in other cases, as a bedroom (Figure 4b).

SAMPLE SIZE

To determine the sample size, non-probability sampling was used in each study period, considering the availability and willingness of users to participate (Table 1).

FIELD STUDY

Surveys were carried out alongside measurements of the house's thermal performance for seven days: five days in the summer (06/01/22 to 01/13/22) and two days in the winter (07/15/22 to 07/16/22). 21 islands of the Uro community were taken as a study due to accessibility. The ASHRAE 55-2017, ISO 7730, ISO 10551, and ISO 7726 standards and norms were used (ANSI/ASHRAE 55, 2017a, pp. 8-19; ISO 7726, 1998, p. 23; ISO 7730, 2005; ISO 10551, 1995) and 78 valid responses of sensation, preference, and thermal acceptability were collected. 50 people were interviewed in 40 dwellings in the summer period and 28 people in 19 dwellings in the winter period. The participants were men and women aged between 18 and 60 years.

DWELLING'S INTERNAL THERMAL PERFORMANCE

Air temperature, relative humidity, globe temperature, and wind speed data were recorded. Two pieces of equipment were placed; a heat stress meter and a hot wire thermo-anemometer (Figure 5b). The measurements were taken with the doors closed, and

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(a)

(b)

Measument content	Operation range	Accuracy
Temperatura de aire (R6250)	0 a 50 °C	±0.8 °C
Resolución		0.1°F/°C
Humedad relativa (R6250)	5 a 95%	>70% HR: ±(3% rdg+1%HR)
Resolución		0.1% HR
Temperatura de globo (R6250)	0 a 80 °C	±0.6 °C
Temperatura de aire (R4500)	0 a 50 °C	±0.8 °C
Velocidad de aire (R4500)	0.2 a 25 m/s	±0.2 m/s
Resolución		fpm: 1m/s, km/h
Diámetro de Globo negro: 2.9" (75mm)		

(c)

Figure 5. Measurement, surveys, and location of equipment. Source: Preparation by the authors.

the recording was done from 9 am to 3 pm. The devices were placed in the center of the room at a height of 1.10 meters from ground level and 0.5 meters from the user (Figures 5a and 5c). The recording was performed at 5-minute intervals for the heat stress meter and 2 minutes for the hot wire thermo-anemometer. In parallel, information on thermal perception was collected from surveys.

After recording the field data, the operating temperature (OT) was calculated, as it is a weighting of the average radiant temperature of the enclosures and the dry air temperature, considering that both contribute to the room temperature with their radiant and convective heat transfer coefficients (Equation 1).

$$t_o = At_a + (1 - A)\, t_r$$

Where: t_o is the operating temperature, A=Constant as a function of the air velocity, t_a is the air temperature (°C), and t_r is the average radiant temperature (°C).

This procedure was carried out for each of the studied houses. The operating temperature (OT) and humidity variables were correlated for data analysis to show scatter plots.

User's body surface area and clothes insulation

To determine the body surface area, information was collected about their previous activity, food intake, and general aspects such as gender and age. Then, the user's height and weight were measured (Table 2), considering the mathematical model of Mosteller (Equation 2).
Regarding the insulation index (Clo), a list of typical

$$Superficie\ corporal\ (m^2) = \sqrt{\frac{altura\ (cm)xpeso\ (kg)}{3600}}$$

Table 2. General information of the users. Source: Preparation by the authors.

Season	Gender	Sample size	Height (cm)	Weight (kg)
Summer	Men	17	165.29	88.37
(January)	Women	33	152.27	77.26
Winter	Men	9	161.22	75.92
(July)	Women	19	151.79	71.24

garments that included 20 options was provided (Figure 6). The data obtained were processed on an Excel spreadsheet, making a sum total per user.

Thermal sensation, preference, and acceptability

For thermal sensation and preference, 7-point rating scale surveys were used, and for acceptability, dichotomous surveys with acceptable and unacceptable ratings were used (Table 3). Between 9 and 14 surveys

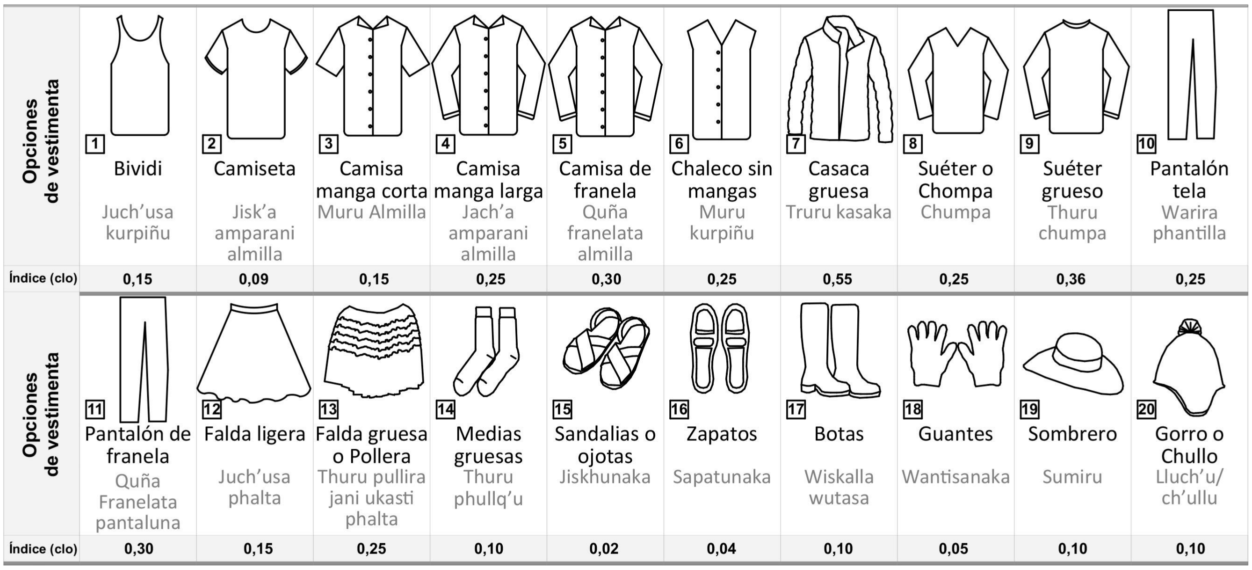

Figure 6. Clothing options. Source: Preparation by the authors and translation into Aymaran by CELEN-UNAP professor, Miriam Jiménez

Table 3. The assessment scale used. Source: Adapted from ASHRAE and ISO 10551 (1995).

Scale	Sensation		Preference		Acceptability
	How are you feeling at the moment regarding temperature and humidity?		How would you rather be right now?		Do you thermally accept this environment at the moment?
	Temperature	Humidity	Temperature	Humidity	Temperature
-3	Very cold	Very dry	Much colder	Much drier	
-2	Cold	Dry	Colder	Drier	
-1	Slightly cold	Slightly dry	Slightly colder	Slightly drier	
0	Neither hot, nor cold	Neither wet, nor dry	No change	No change	Acceptable
1	Slightly warm	Slightly damp	Slightly warmer	Slightly damp	Unacceptable
2	Hot	Humid	Hotter	More humid	
3	Very hot	Very humid	Much hotter	Much more humid	

were conducted daily from 10 a.m. to 4 p.m. Users were asked to perform a sedentary activity (1.2 met) for 20 minutes before responding.

Answers were taken orally and recorded in the questionnaire. A support booklet with the rating scales was used for better visualization. The questions for the answers about thermal sensation and preference regarding temperature and humidity were: How are you feeling right now regarding temperature and humidity? and, how would you rather be right now? For acceptability, the question was: At this moment do you thermally accept this environment? (Table 3). The questionnaire was translated into the Aymaran language (the users' original language) for greater understanding. An Excel spreadsheet was used for data processing. The descriptive statistical method of frequency distribution was used to show the graphs in both study periods.

Personal adjustment strategies

The personal adjustment strategies were used for two conditions (cold and heat) in both males and females. Information was collected by means of 9-point rating scale surveys (ISO 10551, 1995) (Table 4). The information was processed on an Excel spreadsheet. Descriptive statistics of frequency distribution were used to show the graphs. The purpose was to determine which strategy users use most frequently and what modifications they suggest to remain in a state of comfort.

Calculation of neutral temperature

The house's neutral temperature was calculated using the Griffiths method (Griffiths, 1991). The regression constant obtained from the field data was applied for the calculations. This was obtained

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Table 4. Personal adjustments. Source: Preparation by the authors.

En relación al frío, ¿Qué acciones realiza para mantenerse en una temperatura agradable?									En relación al calor, ¿Qué acciones realiza para mantenerse en una temperatura agradable?								
1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
Aumentar la cantidad de ropa.	Usar	Beber bebidas calientes.	Comer comida caliente.		Cerrar la puerta.	Calefactor eléctrico.	Ninguno.	otros	Usar ropas ligeras.		Beber bebidas frías.	Comer comida	Salir al aire libre.	Abrir la puerta.	Usar ventilador eléctrico.	Ninguno.	Otros.

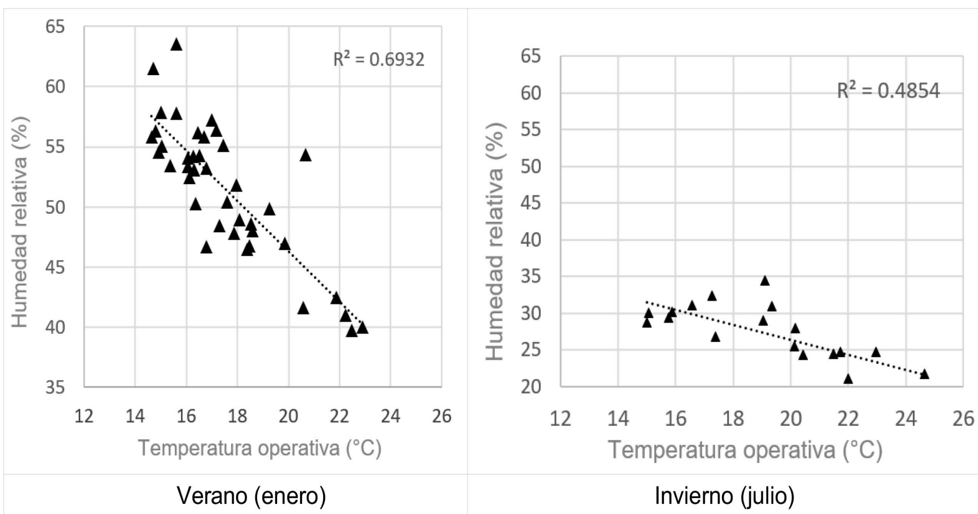

Figure 7. Scatter diagram of the thermal performance of the house. Source: Preparation by the authors.

by correlating the operating temperature variable and the thermal sensation votes using the Pearson coefficient statistic[1]. The constant of 0.33 proposed by (Fanger, 1970) and the universal constant of 0.50 proposed by Humphreys and Nicol (Humphreys & Nicol, 1970) were also used. Considering the dataset collected onsite, the neutral temperature was estimated for the house users. Equation 3 was used to calculate this.

$$T_n = T_o - \left(\frac{VST}{\alpha}\right)$$

Where: Tn is the neutral room temperature (°C); To is the indoor operating temperature (°C); VST is the thermal sensation vote (dimensionless); α is the Griffiths user constant/thermal sensitivity (°C-1).

RESULT

DWELLING'S INTERNAL THERMAL PERFORMANCE

The scatter diagram shows the dwellings' thermal performance in the study periods. The correlation is low for winter and medium for summer, suggesting a tendency for high spread (Figure 7). In the summer, an operating temperature (OT) of 17.50 °C and a predominant relative humidity of 51.5% were observed. On the other hand, in the winter period, the OT is around 19.20 °C, and the relative humidity is 27.16%.

USER'S BODY SURFACE AREA AND CLOTHES INSULATION

The average calculated body surface area for women was 1.80 m², and for men, it was 2.01 m². The average insulation value indicates 1.25 clo for women and 0.86

1 Coefficient that measures the correlation between 2 variables (operating temperature and thermal sensation votes)

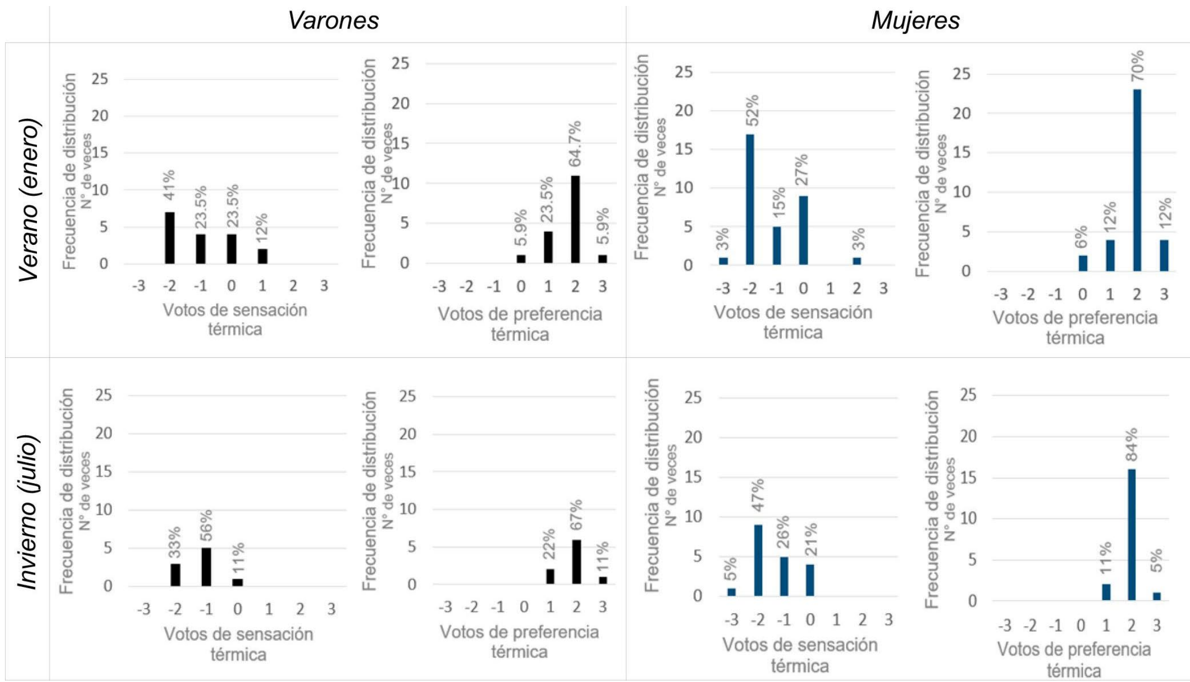

Figure 8. Frequency of thermal sensation and preference votes. Source: Preparation by the authors.

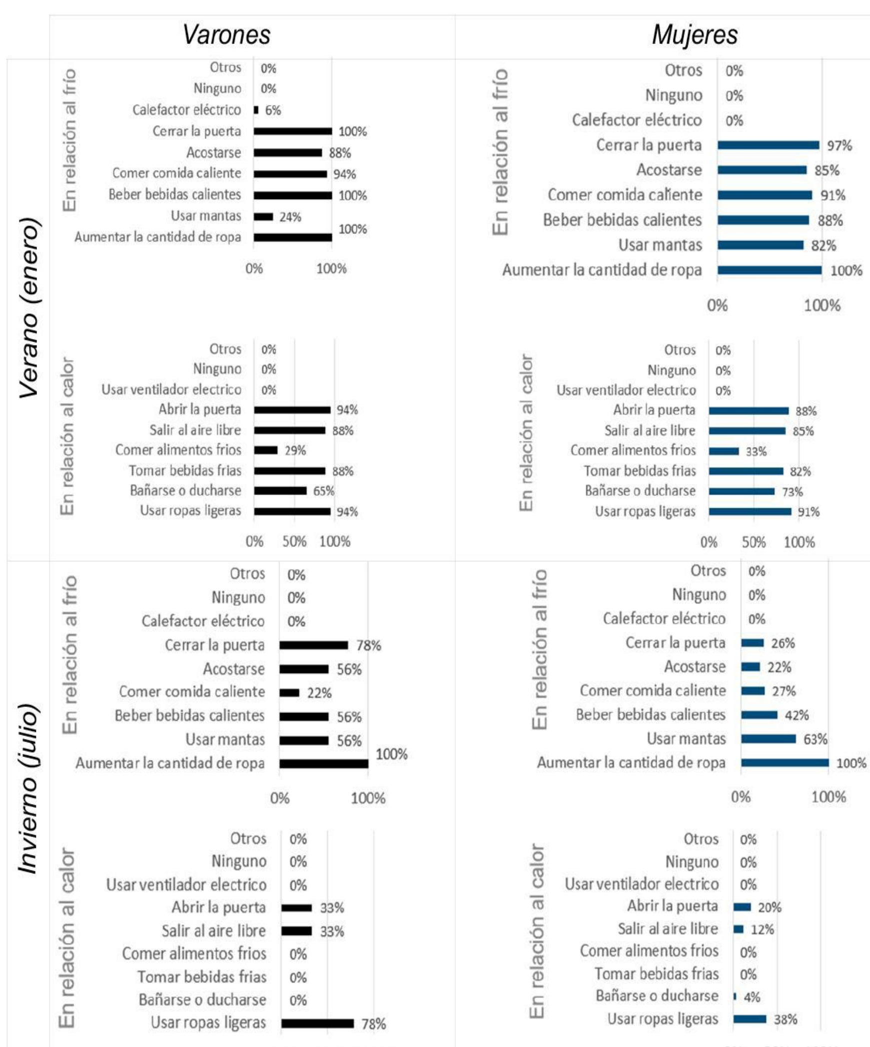

Figure 9. Personal adjustment strategies. Source: Preparation by the authors

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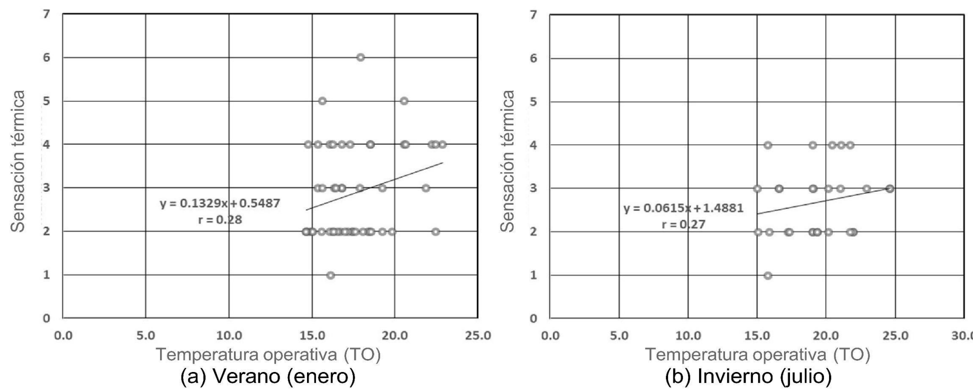

Figure 10. Correlation between the operating temperature and the thermal sensation. Source: Preparation by the authors

Table 5. Neutral temperature and Griffiths constant, SD = Standard deviation, r= correlation coefficient. Source: Preparation by the authors.

Season	Operating temperature (°C)	Griffiths (°C)			
	Mean	0.13	0.06	0.33	0.50
Summer	17.55	25.54	34.87	20.69	19.62
SD		9.97	10.13	4.04	2.96
Winter	19.34	29.50	41.36	23.34	21.98
SD		5.89	6.33	3.29	2.88

clo for men in the summer, while it is 1.01 clo for women and 0.90 clo for men in the winter. This means that in summer, the inhabitants wear more clothes than in winter. This could be because in the summer, there is intense rainfall in the study area, and people need to get warm.

THERMAL SENSATION, PREFERENCE, AND ACCEPTABILITY

The three main thermal sensation assessment scales (Humphreys et al., 2016, cited by Mino-Rodriguez et al., 2018, p. 9) were assumed to be a comfort zone. These consider that a person feels comfortable when the thermal perception responses are (-1) "slightly cold," (0) neutral, or (+1) "slightly warm."

Users, both women and men, concentrate their answers in the category Cold -2, Slightly cold -1, which suggests thermal discomfort because the cold rating is outside the comfort zone. Thus, it is also shown that the thermal preference votes tend towards the category No change 0, Slightly hotter +1, Hotter +2, and Much hotter +3 in both study periods, so a tendency towards warmer environments is observed (Figure 8).

Regarding acceptability, 36% of the respondents indicated that yes, and 64% that they do not accept the environment thermally in the summer season. For the winter season, 28.6% indicated yes and 71.4% no.

PERSONAL ADJUSTMENT STRATEGIES

The strategy regarding the coldest period is to increase the amount of clothing. In this aspect, both men and women coincided in the two seasons studied. The strategies for staying at a cooler temperature in both seasons for both men and women have been to wear light clothes and open the door (Figure 9). The personal adjustments regarding summer and winter are pretty similar for men and women. The occupants point out that changes to the house are necessary. They indicate that they would prefer that the houses be warmer and that less wind enters inside because not all houses have the same amount of Totora blankets.

NEUTRAL TEMPERATURE

The Griffiths constant result for the thermal sensitivity of the house users in the summer period was 0.13 and for winter 0.06. These values are minimal compared to those found in previous field studies (Figure 10). Constants of 0.33 and 0.50 were used, and they are widely used in specialized studies on thermal comfort. The neutral temperature calculated with the constant 0.50 for the summer period was 19.62 °C, and 21.98 °C for winter, with a low standard deviation, so the study assumes these calculated values as neutral temperature (Table 5).

DISCUSSION

The house's internal thermal performance was at an average operating temperature of 17.50 °C in summer and 19.20 °C in winter. Meanwhile, the average outdoor temperature recorded in summer was 3.50 °C and in winter -1.60 °C. The differences are significant, which suggests adopting envelope isolation strategies from the outside.

Thermal sensitivity indicates that users are in discomfort, which may be due to the influence of external weather conditions. More than 60% of users do not accept the room, which suggests a natural desire for warmer environments. According to Xiong et al. (2019), people have to stay indoors with heating equipment in cold areas. However, the Uro community does not have the resources to obtain these mechanical systems, so they wear thick clothes day and night. During the day, the room serves as a kitchen, which is part of the community tradition and can improve its comfort.

Due to the thermal unacceptability, it is necessary to adopt strategies that improve the house's thermal comfort. In cold weather, according to Nie et al. (2019), passive solar heating can reduce the effect of cold and improve energy efficiency, thus improving room temperature. On the other hand, Qiao et al. (2019) point out that the insulation of walls and ceilings with materials with high thermal storage is an adaptive strategy for cold climates. Therefore, the use of solar energy is suggested, along with strategies that involve the improvement of the thermal envelope and airtightness. These include 1) the use of buffer spaces such as corridors, terraced greenhouses, etc., 2) using materials with a large thermal storage capacity, and (3) the dynamic use of housing in the different seasons to take advantage of the climate.

The calculations show a neutral temperature of 19.62 °C for summer and 21.98 °C for winter, with neutral temperatures being determined in similar studies. Rijal et al. (2010) found temperatures of 21.10 °C and 15.30 °C for summer and winter, respectively. Comparatively, the neutral temperature for summer does not present significant differences. However, for winter, the temperature found in this study is higher due to the high solar radiation during the day (5.9 kWh/m^2), which makes it possible for housing to be heated in the daytime schedule. Similarly, Mino-Rodriguez et al. (2018) found an average neutral temperature of 23.40 °C. This value is close to this study and provides consistency to the results. On the other hand, the neutral temperatures found are close to the design temperature of 22 °C according to the ASHRAE 55-2017 standard. However, it is essential to note that the survey's information is for the daytime schedule. Solar radiation is high, especially in winter, so temperatures could drop significantly if the night records were taken. This suggests that thermal neutrality may not be sufficient to identify the thermal comfort needs of users.

Thermal comfort in indoor environments plays a vital role in energy consumption. However, state policies often do not take this into account. This work provides a better understanding of users' thermal comfort for vernacular dwellings in the Uro community, which would help to adopt strategies to improve the dwellings.

The main limitation of the research was the number of people surveyed. This was mainly due to the fact that they did not have time and were not willing to answer the survey. On the other hand, the data collection times were also an impediment because information could only be collected during daylight hours.

CONCLUSIONS

This study highlights users' thermal perception. The vernacular housing is in a state of thermal vulnerability, and the shape must return to the knowledge used in the past, where compactness was taken into account, offering a better response to the climate. The current materiality does not satisfy users' needs despite their adaptive responses to find comfort, such as the constant renewal of the material. In response, the occupants do not thermally accept the dwellings in the daytime, both in the summer and winter seasons. At night, users have to take additional measures to insulate the house, with the envelope being a pivotal point to treat and improve. The neutral temperature value in winter is above the summer period.

The improvements point towards the insulation of the thermal envelope to achieve warmer and drier rooms, the improvement of airtightness with more Totora blankets, and better braiding techniques. This study can be considered an initial study to subsequently conduct studies aimed at the thermal improvement of housing, with in-depth simulations, and technological improvements that involve using Totora, typical of the Uro community.

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ENHANCING ENERGY EFFICIENCY IN GLASS FACADES THROUGH BIOMIMETIC DESIGN STRATEGIES

MEJORA DE LA EFICIENCIA ENERGÉTICA EN FACHADAS DE VIDRIO MEDIANTE ESTRATEGIAS DE DISEÑO BIOMIMÉTICO

MELHORANDO A EFICIÊNCIA ENERGÉTICA EM FACHADAS DE VIDRO POR MEIO DE ESTRATÉGIAS DE DESIGN BIOMIMÉTICO

Büşra Öztürk
Master in Architecture
Research Assistant, Department of Architecture
Selcuk University, Konya, Turkey
https://orcid.org/0000-0001-8177-0653
busra.ozturk@selcuk.edu.tr (Correspondence Author)

Güneş Mutlu-Avinç
Doctor in Architecture
Assistant Professor of what Department or faculty?
Muş Alparslan University, Muş, Turkey
https://orcid.org/0000-0003-1049-2689
gunesavinc@gmail.com

Semra Arslan-Selçuk
Doctor in Architecture
Associate professor and researcher, Department of Architecture
Gazi University, Ankara, Turkey
https://orcid.org/0000-0002-2128-2858
semraselcuk@gazi.edu.tr

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RESUMEN

La industria de la construcción, responsable de una gran proporción del consumo de energía, está buscando soluciones para reducir el consumo de energía. Este estudio propone fachadas biomiméticas para garantizar el confort térmico. En primer lugar, examinó los sistemas de fachadas biomiméticas en la literatura. Luego, analizó los métodos de termorregulación de la naturaleza, el nivel de biomimética y las estrategias desarrolladas por los seres vivos. Como resultado de los análisis, se amplió la información biológica relativa a los tres fenómenos seleccionados y se determinó cómo transferir el método de biomimética que podría estar en la envolvente del edificio. Se realizaron simulaciones de energía en la fachada de vidrio del baño Süleyman Pasha para evaluar la eficiencia energética de la envoltura. Se encontró que los métodos inspirados en la naturaleza contribuyeron significativamente al consumo de energía del edificio cuando se diseñaron los resultados de simulación de la fachada.

Palabras clave
biomímesis, diseño de fachadas, eficiencia energética, termorregulación.

ABSTRACT

The building industry, responsible for a large proportion of energy consumption, is looking for solutions to reduce energy consumption. This study proposes biomimetic facades to ensure thermal comfort. Firstly, it examined biomimetic façade systems in the literature. Then, it analyzed the thermoregulation methods of nature, the level of biomimicry, and the strategies used by living things. As a result of the analyses, biological information regarding the three selected phenomena was expanded upon, determining how to transfer the biomimicry method to a building envelope. Energy simulations were conducted on the glass façade of the Süleyman Pasha Bath to evaluate the envelope's energy efficiency. It was found that nature-inspired methods significantly contributed to the building's energy consumption when examining the simulation results of the façade designed.

Keywords
biomimicry, facade design, energy efficiency, thermoregulation.

RESUMO

A indústria da construção, responsável por grande parte do consumo de energia, procura soluções para reduzir o consumo de energia. Este estudo propõe fachadas biomiméticas para garantir conforto térmico. Primeiramente, examinou sistemas de fachadas biomiméticos na literatura. Em seguida, analisou os métodos de termorregulação da natureza, o nível de biomimética e as estratégias desenvolvidas pelos seres vivos. Como resultado das análises, a informação biológica sobre os três fenômenos selecionados foi ampliada e determinada como transferir o método de biomimética que poderia ser para a envolvente do edifício. Simulações energéticas foram realizadas na fachada de vidro do Süleyman Pasha Bath para avaliar a eficiência energética do envelope. Verificou-se que os métodos inspirados na natureza contribuíram significativamente para o consumo de energia do edifício quando os resultados da simulação da fachada projetada.

Palavras-chave:
biomimética, design de fachadas, eficiência energética, termorregulação.

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INTRODUCTION

Increasing global energy consumption and changing climate conditions have recently been on the agenda of many sectors, particularly the building sector. According to the International Energy Agency (IEA), the building sector accounts for one-third of total energy consumption (International Energy Agency, 2019), and most of the energy consumed in construction comes from heating, cooling, and ventilation (HVAC) systems (Engin, 2012). In particular, where large, glazed areas are used on facades, the cooling load increases during the day, and the heating load increases at night. This situation leads to high levels of energy consumption. For this reason, the construction sector is focusing on methods that use renewable energy sources to reduce energy consumption and harmful gas emissions and draw attention to energy-efficient building design. Along this line, energy-efficient building design aims to provide natural ventilation by directing daylight and reducing the required heating and cooling load (Pacheco ve diğ., 2012). Under this, thermal comfort in buildings is provided by increasing the efficiency obtained from natural resources such as heat, light, rain, and wind with passive energy-efficient methods and creating a climate-sensitive design (Kim ve Torres, 2021).

It can be said that nature also has much to offer in terms of developing energy-efficient proposals such as thermal regulation and climate-sensitive design to increase the efficiency of natural resources such as heat, light, rain, and wind. In this context, the thermal regulation methods used by living creatures in nature to ensure energy efficiency are being analyzed and applied to architecture. In nature, thermal regulation is referred to as thermoregulation, which protects an organism's body temperature from changing external factors and ensures it remains within an appropriate range (Farchi Nachman, 2009). In this context, biomimetic designs/materials are being developed by examining examples of thermoregulation, learning from nature, and benefiting by developing technology. By examining the physiology, morphology, and behavior of living creatures in nature, many methods have been developed, and solutions can be found to problems encountered in structures.

The fact that nature responds to the problems it encounters by finding the most appropriate solutions has led human beings to study nature throughout history. Practical solutions are offered to many daily life problems by learning from nature. This method, called bio-informed design/biomimicry/biomimetics/biodesign, focuses on assimilating the role of nature and producing functional solutions with the information obtained. This approach is on its way to becoming a branch of science that supports the process of learning from, adapting to, and applying the qualities of living or non-living organisms. Although this method is defined as 'emulating strategies' (Zari, 2007), it is developing as a field that produces innovative designs that contain solutions for humanity's problems by turning to biological solutions (Mutlu Avinç & Arslan Selçuk, 2019).

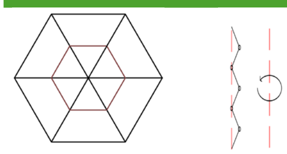
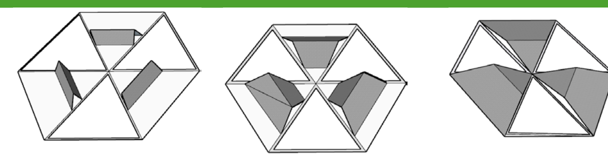
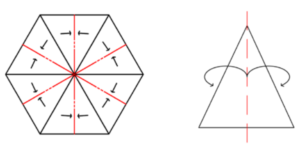
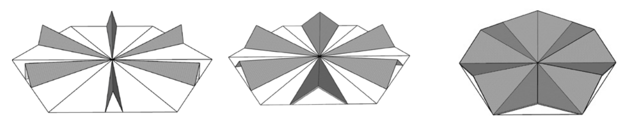
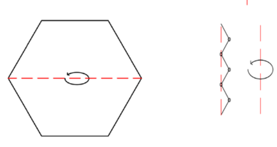
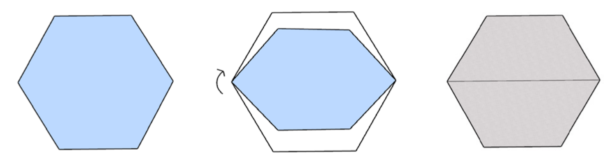
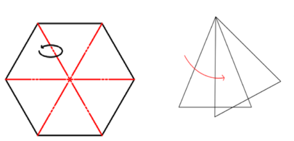
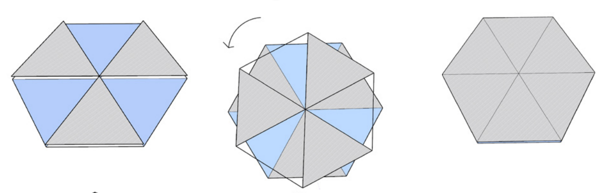
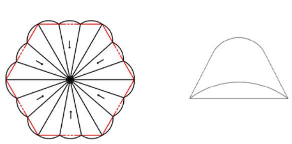
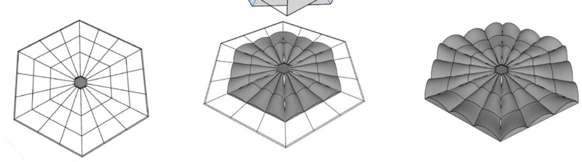
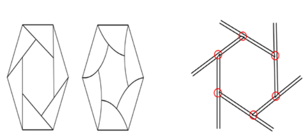
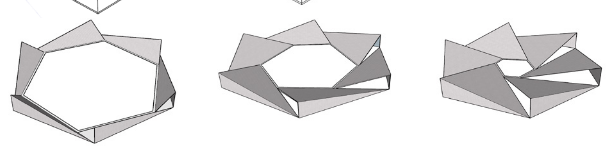
Facades are important energy-regulating components directly exposed to external factors and in contact with renewable energy sources (Tabadkani et al., 2021). For this reason, the literature has recently widely discussed energy-efficient building design proposals that can thermoregulate façade design with biomimetic approaches. For example, Badarnah et al. (2010) designed the stoma brick as a façade material by considering it as a thermal barrier to protect the heat of the façade and distribute it appropriately. This design proposes a building envelope with a cooling system for arid and hot climate regions. Kim et al. (2023) designed a kinetic façade using daylight-sensitive and innovative materials (shape memory alloys and actuators) in a pneumatic system. The biomimetic façade design, inspired by a hexagonal honeycomb module and a plant stoma feature, was analyzed by testing the simulation results and a prototype.

On the other hand, the façade study developed by Kalatha (2016) presents proposals for improving indoor comfort and ventilation. Sensitive panels that can change shape according to the temperature and physical factors have been proposed in the façade design, which is based on a working principle of stomata. In the study by Aly et al. (2021), a prototype façade was developed using water retention capacity with the capillary effect found in the skins of thorny devil lizards living in the desert climate. In a study by Lopez et al. (2017), a biomimetic approach is proposed for glass facades with high energy losses by considering the relationship between architecture and biology. By creating a dataset of plant adaptations, a methodology is proposed that reflects the adaptation of biological principles to architectural resources and new technologies. In their study, Sheikh and Asghar (2019) present a biomimetic adaptive facade design to improve the energy efficiency of high-rise glass facades in regions with hot and humid climates, reducing the energy load by 32%. In a study by Paar and Petutschnigg (2016), the issue of façade greening was addressed by considering the modular growth of prairie dog burrows and mussel colonies. To provide a solution to the urban heat island effect, the increased energy consumption due to global warming, and the increasing heating of cities, a façade design concept with natural ventilation and cooling functions has been developed based on biomimetic principles.

Another study by Faragalla and Asadi (2022) presents a methodology that includes different typologies, methods, and conceptual frameworks for adaptive facade design, focusing on biomimetic principles. This research highlights the importance of energy efficiency in the early stages of design. Meanwhile, Kuru et al. (2019) touched on the importance of biomimetic adaptive building envelopes for energy efficiency, and through characterization and strategies, they examined current technologies through a comparative analysis. In their study, Sommese et al. (2022) investigated sensitive and intelligent building envelopes. This study aims to draw attention to the potential of nature's vast database by critically examining current technology in terms of energy efficiency.

This study addressed in this article was based on the hypothesis that "a biomimetic solution to the problem of

Table 1. Facade Module System Mechanisms - Alternatives. Source: Prepared by the authors

Module Form	Movement Axis	Movement Direction and Type	System Status - On	System Status - Half Open	System Status - Off	Structure Reference Sample
		Opening to the sides Folding system				CJ Blossom Park
		Folding along the axis Folding system				Kiefer Technic Showroom / Al-Bahr Towers
		Rotation around center Rotation				ThyssenKrupp Quartier Essen Q1
		Rotation around center Rotation				RMIT Design Hub
		Gathering Toward the Center Pneumatic System				Media-TIC Build-ing
		Shift along axis Sliding System				Institut du Monde Arabe

indoor thermal comfort and excessive energy consumption caused by the use of glass facades can be proposed by plants and animals found in nature, and improvements in energy consumption can be achieved." For this purpose, the study looked at natural thermoregulation principles and strategies to prevent overheating (during the day) and overcooling (at night). Living things were reviewed using the keywords "reflection, heat prevention, absorb radiation, reduce irradiation, overheating, heat regulation" in the AskNature database, and principles have been derived by studying these living things' thermoregulatory methods and working mechanisms. Based on these principles, solutions have been sought to prevent overheating and overcooling caused by temperature changes in glass façade systems. For this purpose, five plants and five animals with thermoregulation methods for heat distribution and gain were discussed, and a double-façade glass system has been designed to be sustainable and energy-efficient, taking inspiration from living things. The study was analyzed using an energy simulation program, an innovative module in the glass facade system designed by learning from nature.

FACADE MODULE SYSTEM MECHANISMS - ALTERNATIVES

In today's evolving technological conditions, essential advances have been made in materials and techniques. Thanks to these developments, kinetic façade designs, which adapt to the façade and change according to the environmental conditions, are coming to the fore. Before deciding on the system design, this study studied the kinetic façade module using techniques developed on the regular hexagonal façade module, one of the Voronoi diagrams. Alternatives for daylight-sensitive opening and closing mechanisms were determined using the hexagonal façade module. In deciding these alternatives, kinetic façade designs in the literature and buildings with adaptive envelopes were examined. It can be seen that specific techniques such as sliding, folding, rotating, and pneumatic operation are widely used as opening and closing mechanisms in façade modules. These techniques model and express the fully closed, semi-open, and fully open states of façade modules designed for different systems. The kinetic façade, designed

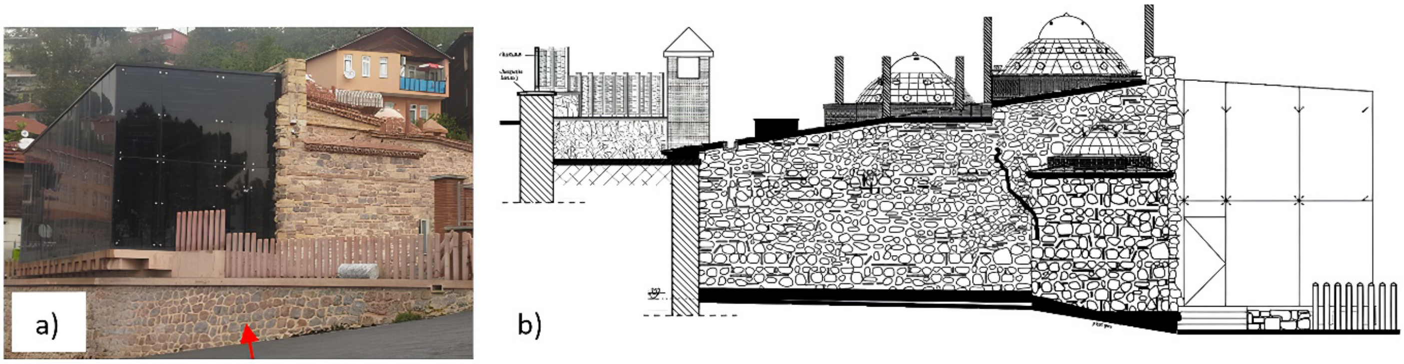


Figure 1. a) Süleyman Pasha Bath sections after repair b) Suleyman Pasha Bath Northwest Facade. Source: Güner Design - Architect Gülhan Dilaver.

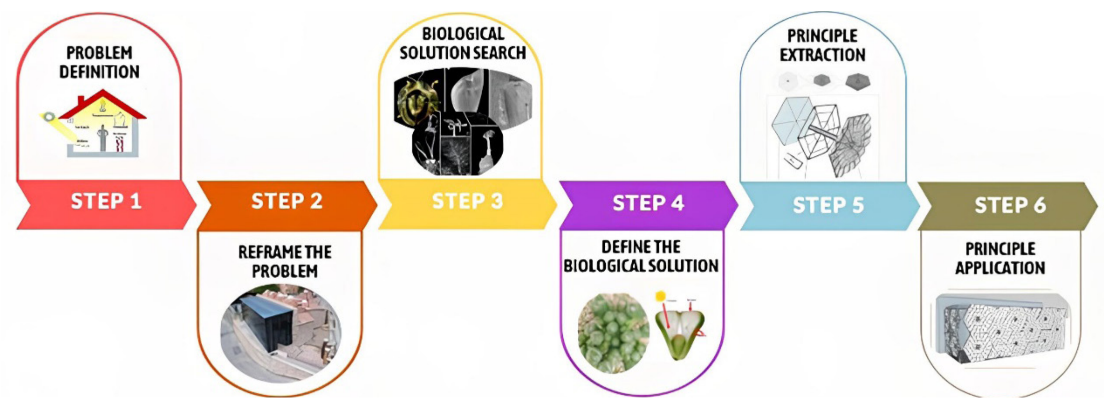


Figure 2. Problem-oriented approach used in biomimetic research. Source: Helms, Vattam, & Goel, 2009, edited by the Author.

according to biomimetic principles and using technically advanced materials, is expected to solve overheating and cooling problems by controlling daylight access to the interior (Table 1).

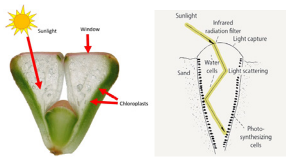
MATERIALS AND METHODS

The Suleyman Pasha Bath in the Akçaova district of Izmit, the case study, was built during the Ottoman period. The Suleyman Pasha Bath is the earliest surviving Ottoman structure in Izmit. Although part of the structure has been demolished recently, most of the baths have survived to the present day. The right to evaluate and use the bath for socio-cultural purposes has been transferred to the General Directorate of Foundations with the agreement of Kocaeli Metropolitan Municipality. Work has been carried out to ensure that the ruined bath, which was left unrestored for many years, regains its function and is used again (Polat et al., 2010). Built in the early Ottoman period, the bath has a traditional double bath designed separately for men and women. As an architectural feature, the bath comprises changing rooms, warm rooms, and hot rooms. However, since the changing room was demolished, this has been rebuilt and converted into a cafe (Kocaeli Cultural Envanteri, 2011) (Figure 1).

The glass façade of the cafe area at the Suleyman Pasha Bath, which has been given a contemporary addition as part of the restoration project, was evaluated as part of this study. The cafe is located on the south side and experiences overheating in summer and overcooling issues in winter, requiring high energy consumption to ensure indoor comfort. It has an essential problem that HVAC systems cause excessive energy consumption to provide the necessary comfort conditions for the space. This study proposes a biomimetic glass façade system that will reduce energy consumption while increasing indoor comfort conditions and can be applied as a secondary skin to the existing façade.

Within the scope of this study, biomimetic solutions were investigated to increase the comfort level of the café area's glass façade for the Süleyman Pasha Bath and reduce the energy consumed. As all living organisms can control energy losses and gains by thermoregulating their systems, a solution to the identified problem was sought using methods learned from nature. In this process, the problem-oriented approach method, one of the biomimicry approaches, was used. First, the process of identifying the problem was completed. Then, solutions to the identified problem were sought from nature, certain principles were derived, and a solution was proposed. In addition, the façade designed in the study was analyzed in an energy simulation program (Design Builder) to see the changes in heating and cooling load according to the material qualities. Finally, a solution was proposed for the problem, which was an architectural façade solution for

Table 2. Examination of the biomimetic solutions used in the design. Source: Prepared by the authors.

Reference	 Cactus Kingdom (n.d.)	 Asknature (n.d.)	 (Çağlar, 2020)
Method	Heat Prevention Heat Preservation Behavioral Adaptation	Heat Gain Heat Preservation Physical Adaptation	Heat gain Morphological Adaptation

the contemporary extension of the historical bath in Kocaeli (Figure 2).

CASE STUDY: BIOMIMETIC GLASS FACADE SYSTEM DESIGN

Thermoregulation methods for living things have been studied to address the overheating and overcooling problems in glass façade systems. Living things use three approaches to achieve thermoregulation: heat conservation, heat gain, and heat prevention. This study searched the AskNature database for keywords related to plants and animals. As a result of the research, creatures with a method for preventing overheating and heat gains were examined. Living beings in arid and desert climates have developed different strategies to avoid overheating. These strategies are generally seen in plants as adaptations that regulate heat loss by opening and closing stomata or morphological characteristics. On the other hand, in animals, thermoregulation has been observed by regulating color changes and surface area ratios according to skin characteristics. In the second part of the study, the thermoregulatory strategies of plants and animals were analyzed. Plants such as *Fenestraria aurantiaca,* English ivy, giant ground grass, alpine edelweiss, and the kukumakranka plant were found, as were animals such as turtle beetle, chameleon, morpho butterfly, bumblebee, and the hissing cockroach.

In the search for a biomimetic solution to the study's problem, adaptations for both heat gain and heat prevention were discussed. While a heat prevention function is required in glass façade systems in buildings during the day, a heat gain function is needed when the temperature drops at night. The aim is to design a double skin façade that reflects much of the daylight during the day and acts as an insulating layer at night. Fenestraria and giant marmot plants were considered as solutions among ten creatures whose thermoregulation methods were studied. The Fenestraria plant is thought to be a solution to the problem of excessive sunlight that the building is exposed to during the day, as it captures and cuts excess light in the desert climate and acts as a lens. It has also been suggested that the giant grass protects its inner leaves by closing when the temperature drops in the high parts of the mountains, acting as an insulating layer. The fact that this plant opens and closes depending on the temperature has led to a façade design that will act as insulation by closing a building's heat-sensitive facades. In addition, the modules to be designed are inspired by the Voronoi pattern seen on the shell and skin surfaces of creatures found morphologically in the mathematics of nature. Kahramanoğlu and Alp (2021), as a result of the daylight analysis of the façade systems designed in alternative shapes, showed in their study that when the Voronoi diagram is used, the light incidence on the façade is higher and can be controlled at the desired level by adjusting the thickness of the lines. For this reason, it was decided to use regular hexagons from the Voronoi diagrams in the glass façade module to be designed in the study (Table 2).

The design process examined mechanisms studied in nature and their methods applied to the façade. The method of directing and controlling excess light from the Fenestraria plant used in the façade design was used to solve the overheating problem in the façade module. In addition, the ability of the giant ground grass plant to close itself when the temperature drops and protect its system from the effects of frost was considered in the design. According to the principles learned from these two projects, it was decided to use electrochromic glass to direct excess daylight. In addition, the pneumatic system, made of ETFE material, which closes at low temperatures at night, is integrated as a double façade. Among the alternative façade modules shown in Table 1, a pneumatic system was designed with an actuator that closes at night at low temperatures and collects heat during the day (Figure 3).

As part of the study, a façade system that behaves like fenestraria and giant ground grasses was designed, adopting thermoregulatory principles. This system design aims to reduce the heating and cooling loads caused by glass façade systems. The pneumatic system, which is closed during the day, is activated at night and acts as a second façade covering the façade surface, protecting it from excessive cooling. In addition, the electrochromic glass used on the façade during the day will ensure that light above a specific wavelength is reflected, preventing overheating. The biomimetically designed double skin façade system was applied to the glass façade system in the contemporary annex ('cafe space') of the historic Suleyman Pasha Bath, and the energy simulation analyses were carried out (Figure 4). In the energy simulation calculations, the façade system information, consisting of

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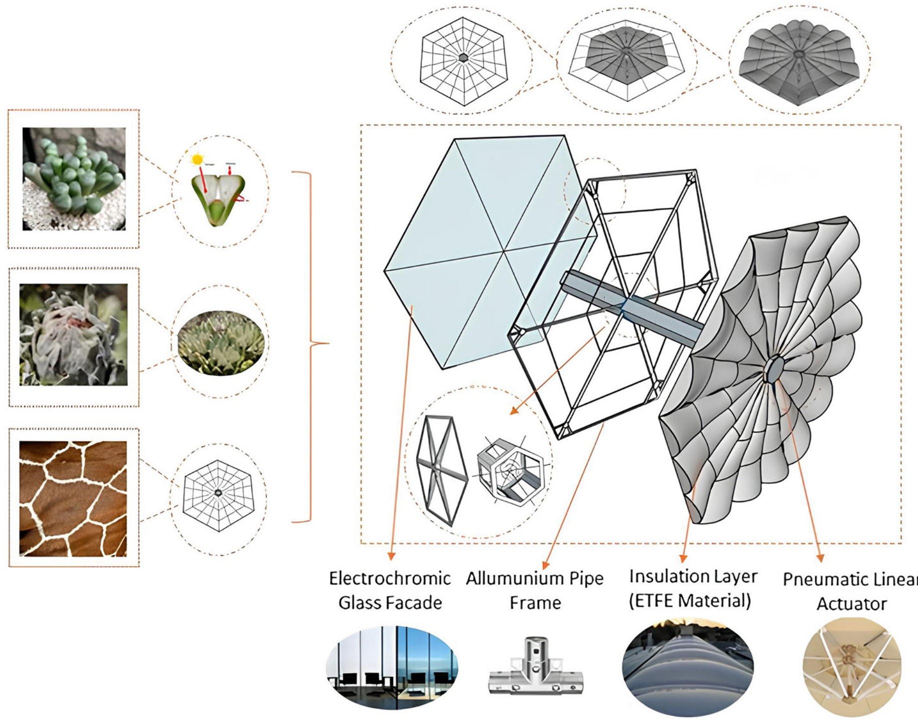

Figure 3. The double-skinned facade module was designed using a biomimetic approach. Source: Prepared by the authors.

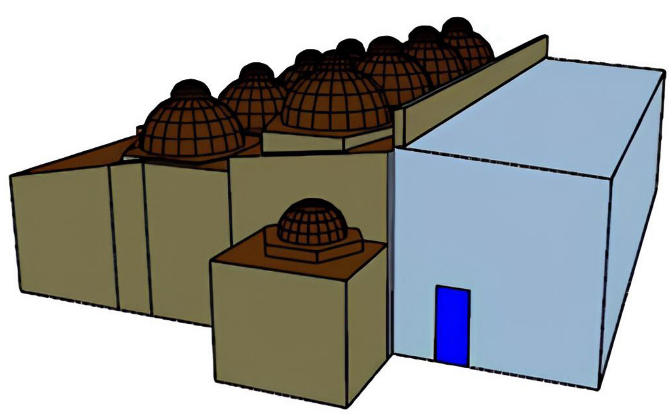

Figure 4. The Süleyman Pasha Bath model created in the Design-Builder program Source: Öztürk, 2023.

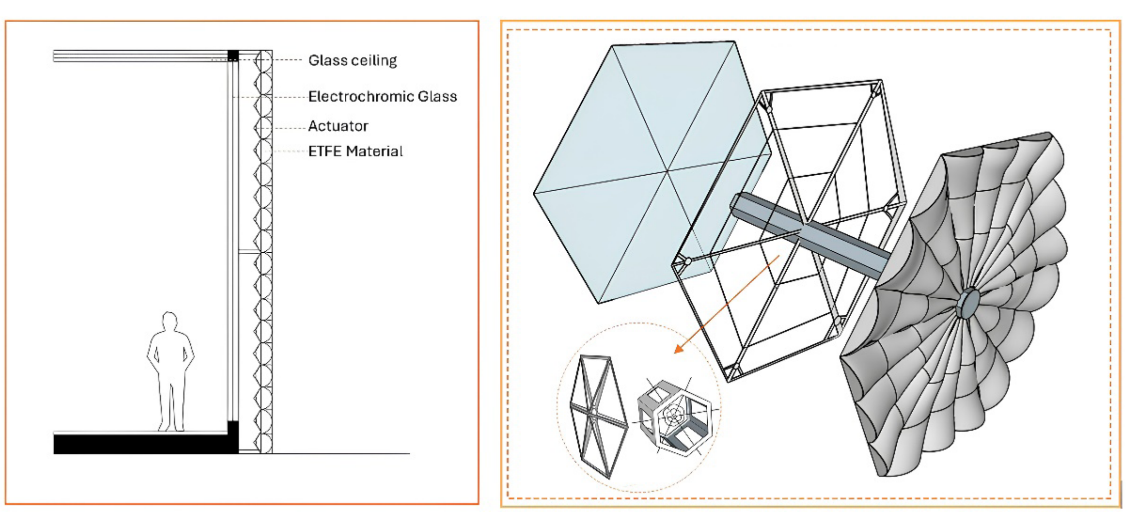

Figure 5. Application of the glass façade system to the Suleyman Pasha Bath Cafe space. Source: Prepared by the authors.

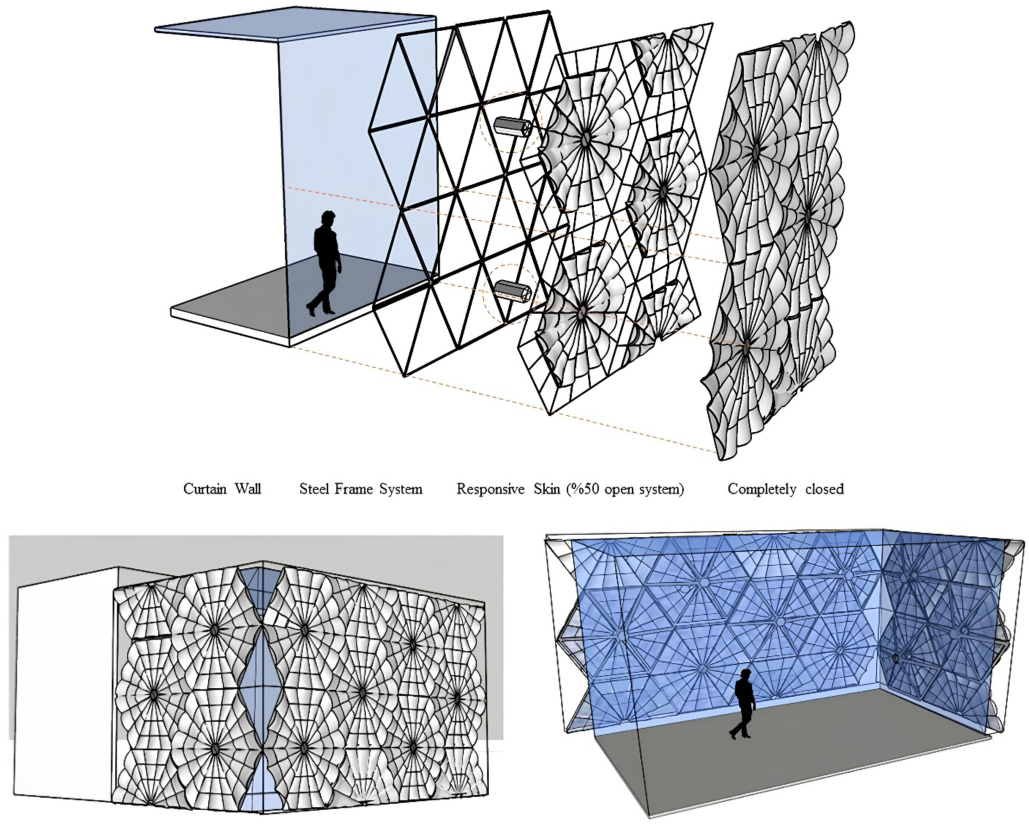

Figure 6. Application of the glass façade system to the cafe area of Süleyman Pasha Bath. Source: Prepared by the authors.

three different scenarios, was input into the program, and its effect on the heating and cooling load results was evaluated. The first scenario was calculated using the existing material properties of the building (Öztürk, 2023). The simulation results were obtained by incorporating the single-layer electrochromic glass system into the second and double-layer electrochromic glass façade material information in the third scenario (Figure 5 and Figure 6). The material properties of the electrochromic glass façade system were obtained from the Lee and Tavil (2007) study on electrochromic glass material performance and defined in the Design-Builder program. The total energy consumption values of the bath building were compared using the material properties determined and achieved in the Design-Builder program and by inputting the climate data of Kocaeli (Table 1 and Table 2).

The thermal properties of the materials used in the existing Suleyman Pasha Bath glass façade system and the thermal values of the proposed alternative single and double-story electrochromic glass façade system are shown in Table 3 below. Three different results were obtained by entering the climate data of Kocaeli province using three different materials in the Design-Builder program. Case 1 of these three scenarios is the heating, cooling, and total energy load analysis obtained by defining the existing material properties of the bath structure. In Case 2, the thermal properties of the single-layer electrochromic glass material in the glass material of the Cafe space of the building were defined in the program, and energy analyses were carried out. In Case 3, the simulation was run by defining the properties of the double-layered and reflective coated electrochromic glass material for the glass façade system. The electrochromic glass material types and thermal properties recommended in the study were taken from the study by Lee and Tavil (2007). They were defined in the program by adding the building's material properties and climate data (Table 3).

DISCUSSION

Increasing energy demand due to the construction sector and the energy of the systems used for occupant comfort significantly increase energy consumption. For this reason, attempts to reduce building energy consumption and ensure thermal comfort indoors are increasing. This study discusses the problem of overheating and cooling in glass façades.

The double-skin glass façade system proposed in the study was designed with a temperature-sensitive pneumatic system. The electrochromic glass was recommended to reduce the adverse effects of excessive light on the interior during the day. Simulation analyses were carried out on two types of electrochromic glass used in the design: single-layer and double-layer. It is expected that the designed biomimetic glass façade system will provide a solution to the daytime overheating problem of the café area of the Süleyman Pasha Bath. It is also expected that the pneumatic system, which forms the second layer of the façade system, will close at night and act as insulation for the glazing material, preventing

Table 3. Thermal properties of glass facade systems and values defined in the program. Source: Prepared by the authors.

Buildings	Materials	Thickness (cm)	Thermal Conductivity λ (W/mK)	U value (W/m2K)
Cafe Space Wall analysis of the building (CASE 1) (Öztürk, 2023)	Tempered silver gray	0,8 cm	0,052	U: 1,70
	Air gap	0,05 cm	R: 0,11	
	Tempered laminated glass	0,8 cm	0,052	
Alternative Glazing System Wall Analysis (CASE 2)	Electrochromic Glass	1 cm	0,010	U: 1,07
	Single Layer Clear Glass		Solar Heat Gain Coefficient (SHGC): 0,69 Glass Transmittance (VT): 0,71 (Lee and Tavil, 2007)	
Recommended Glazing System Wall Analysis (CASE 3)	Electrochromic Glass Double Layer Reflective coating	2 cm	0,011 SHGC: 0,17 VT: 0,10 (Lee and Tavil, 2007)	U: 0,57

Table 4. Total heating and cooling load values according to energy simulation results

	CASE 1	CASE 2	CASE 3
Heating Load (kWh)	23,357.71	19,549.33	15,876.61
Cooling load (kWh)	13,849.10	12,347.49	9,476.18

excessive cooling in the interior. To see the effect of the facade system designed for this purpose on the total annual heating and cooling load of the bath structure, it was modeled in the Design-Builder program, and the material definitions and equipment used for space heating were processed in the program. The annual energy loads were obtained by creating three scenarios through the model. According to simulation results, the highest heating and cooling load is achieved in Case 1. In case 2, significant improvements were observed in both heating and cooling loads using single-layer electrochromic glass material. The total annual energy load of the space decreased by 16% compared to Case 1. When the simulation results are examined, a decrease in the total energy consumption of the building of approximately 32% is observed between Case 1 and Case 3 (Table 4).

CONCLUSION AND RECOMMENDATIONS

To reduce energy consumption in the building sector on a global scale, it is essential to focus on energy-efficient designs and to carry out interdisciplinary studies in this direction. Façade design studies, particularly those inspired by natural systems, have reached a critical point in the building envelope's energy efficiency. As the building envelope acts as a buffer between interior and exterior spaces, significant energy gains can be achieved by learning from nature and designing systems that respond sensitively to daylight. In this study, the hypothesis that biomimetic solutions could solve the problem of heating and cooling loads in glass façade systems in buildings has been confirmed as a result of investigations and simulation analyses. This study investigated plants and animals from nature to address the overheating and overcooling problems in glass façade systems in locations with high-temperature differences. An architectural façade solution was proposed based on the thermoregulatory principle of the two plants selected as the solution for the façade system. Studies have been carried out on designing the façade using plants that respond to excessive heating and cooling. The proposed façade system will be able to reflect excess light during high daytime temperatures. It will also reduce the cooling load demand by reducing the use of air conditioning in the interior. In addition, the system will switch off at night and act as an insulating layer on the façade during harsh weather conditions when the temperature drops. While electrochromic glass material is recommended to solve overheating in the double facade system, the pneumatic system design using ETFE material, which is activated at low temperatures, will form the insulating layer.

As part of the study, simulation analysis was carried out to test the designed façade system and to see the energy consumption rate. The designed façade was analyzed on a building located in the Kocaeli province, which gained a cafe space (contemporary addition) in the glass façade system on the south façade after restoration. Since the contemporary addition to the building is located on the south side, the indoor comfort in summer is negatively affected, resulting in overheating. When the simulation results were examined in three different situations based on the properties of the glass material, a 32% improvement in the total energy load was observed using a double-layer electrochromic glass façade. The search for solutions to architectural problems by analyzing nature leads, at this point, to the study of innovative biomimetic material designs. In this way, sustainable and energy-efficient solutions can be offered with an interdisciplinary approach.

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OPTIMIZATION IN THE DESIGN OF CONCRETE MIXES FOR THE SUSTAINABILITY OF A SOUTH AMERICAN METROPOLITAN AREA BY IMPLEMENTING MATERIAL LIFE CYCLE ANALYSIS

OPTIMIZACIONES EN EL DISEÑO DE MEZCLAS DE CONCRETO PARA LA SOSTENIBILIDAD DE UN ÁREA METROPOLITANA DE SUDAMÉRICA IMPLEMENTANDO ANÁLISIS DE CICLO DE VIDA DE MATERIALES

OTIMIZAÇÕES NO PLANEJAMENTO DE MISTURAS DE CONCRETO PARA A SUSTENTABILIDADE DE UMA ÁREA METROPOLITANA NA AMÉRICA DO SUL, IMPLEMENTANDO A ANÁLISE DO CICLO DE VIDA DOS MATERIAIS

Andrés Felipe Restrepo-Ramírez
Magíster en Construcción
Profesor auxiliar, Escuela de Construcción, Facultad de Arquitectura
Universidad Nacional de Colombia, Medellín, Colombia
https://orcid.org/0000-0002-1178-7780
anfrestrepora@unal.edu.co (Autor de Correspondencia)

Carlos Andrés Rúa-Machado
Master Bussiness Administration
Profesor Asistente, Escuela de Construcción, Facultad de Arquitectura
Universidad Nacional de Colombia, Medellín, Colombia
https://orcid.org/0000-0003-4174-5087
caruama@unal.edu.co

Yhan Paul Arias-Jaramillo
Magíster en Ingeniería de Materiales y Procesos
Profesor Asociado, Escuela de Construcción, Facultad de Arquitectura
Universidad Nacional de Colombia, Medellín, Colombia
https://orcid.org/0000-0002-8988-6295
ypariasj@unal.edu.co

RESUMEN

El análisis de Ciclo de Vida ACV, es una metodología que identifica los aspectos ambientales y los impactos potenciales asociados con un producto mediante la compilación de un inventario de las entradas y salidas del sistema para su optimización, planificación estratégica e implementación de políticas sostenibles. En el ámbito de la producción de concretos, se han utilizado diversas técnicas de optimización y su impacto en el diseño de mezclas como análisis multicriterio, modelos estadísticos, materiales cementantes suplementarios y algoritmos de optimización. Este trabajo aplica el ACV a la producción de concreto el Área Metropolitana del Valle de Aburrá, Colombia, con la hipótesis de optimizar las proporciones, sin agregar aditivos ni adiciones especiales, se puede reducir las emisiones de CO_2 y el consumo de energía. Utilizando la metodología ACI 211, se diseñaron mezclas de concreto y se evaluaron sus impactos ambientales. Los resultados muestran que el uso de agregados gruesos de mayor tamaño reduce el consumo de cemento, disminuyendo las emisiones de CO_2 hasta un 15%. La mezcla óptima no sólo es más económica, sino también de menor impacto ambiental. Las conclusiones indican que es posible compatibilizar la eficiencia económica, promoviendo la disminución en la huella de carbono.

Palabras clave
análisis de ciclo de vida ACV, sostenibilidad, optimización de agregados, producción de concreto

ABSTRACT

Life Cycle Assessment (LCA) is a methodology that identifies a product's environmental aspects and potential impacts by compiling an inventory of system inputs and outputs for optimization, strategic planning, and implementing sustainable policies. Several optimization techniques and their impact on mix design have been used in concrete production, such as multi-criteria analysis, statistical models, supplementary cementitious materials, and optimization algorithms. This work applies LCA to concrete production in the Metropolitan Area of the Aburrá Valley, Colombia, with the hypothesis that optimizing proportions without adding special additives can reduce CO2 emissions and energy consumption. Concrete mixes were designed using the ACI 211 methodology, and their environmental impacts were evaluated. The results show that using larger coarse aggregates reduces cement consumption, decreasing CO2 emissions by up to 15%. The optimal mix is not only cheaper but also has a lower environmental impact. The conclusions indicate that it is possible to make economic efficiency compatible with promoting a lower carbon footprint.

Keywords
life cycle assessment LCA, sustainability, aggregate optimization, concrete production

RESUMO

A Avaliação do Ciclo de Vida (ACV) é uma metodologia que identifica os aspectos ambientais e os possíveis impactos associados a um produto por meio da compilação de um levantamento das entradas e saídas do sistema para otimização, planejamento estratégico e implementação de políticas sustentáveis. No campo da produção de concreto, várias técnicas de otimização têm sido usadas e seu impacto no projeto de mistura, como análise multicritério, modelagem estatística, materiais cimentícios suplementares e algoritmos de otimização. Este trabalho aplica a ACV à produção de concreto na Área Metropolitana do Vale de Aburrá, na Colômbia, com a hipótese de que a otimização das proporções, sem a adição de aditivos ou aditivos especiais, pode reduzir as emissões de CO2 e o consumo de energia. Usando a metodologia ACI 211, as misturas de concreto foram projetadas e seus impactos ambientais foram avaliados. Os resultados mostram que o uso de agregados grossos maiores reduz o consumo de cimento, reduzindo as emissões de CO2 em até 15%. A mistura ideal não é apenas mais econômica, mas também tem um impacto ambiental menor. As conclusões indicam que é possível compatibilizar a eficiência econômica e, ao mesmo tempo, promover uma redução na pegada de carbono.

Palavras-chave:
análise do ciclo de vida ACV, sustentabilidade, otimização de agregados, produção de concreto

INTRODUCTION

Concrete production is a fundamental part of the industrial construction sector. However, its environmental impact has become an object of increasing concern in a world searching for sustainable practices due to the overexploitation of resources and the damage to multiple ecosystems. Different research projects have shown that concrete is one of the main generators of GHG (Belaïd, 2022a; Das et al., 2023; Mocová et al., 2019; Watari et al., 2023). The global demand for this material has quadrupled in the last three decades, leading to an increase in CO_2 emissions that has exacerbated the shortage of sand and social conflict (Watari et al., 2023). In this context, LCA becomes an essential tool for evaluating and developing criteria that help mitigate the adverse environmental impacts generated by producing concrete mixtures. Although there are challenges and discrepancies in the measurement of the environmental impact of concrete due to the lack of a standardized LCA methodology, the studies provide criteria for making progress in this framework (Jayasuriya et al., 2023). These discrepancies arise from factors such as scope definition, inventory data, impact assessment, and interpretation (Hafez et al., 2019). However, some standards, such as the NTC-ISO 14044 (ICONTEC, 2021), are implemented in some Latin American countries, especially in Colombia. This standard establishes a systematic and holistic approach to evaluating the environmental impacts of processes and products in a structured way.

ISO 14044 defines this process as the collection and evaluation of inputs, outputs, and potential impacts of a production system for a product through its life cycle. This links the LCA with other approaches, such as Lean Construction (Koskela et al., 2019), and opens up the possibilities of understanding and articulation. Table 1 summarizes some contributions aimed at finding implementations based on ISO 14044.

Through their methodological and numerical models, these tools provide crucial elements for the environmental challenges humanity faces (Boccia & Sarnacchiaro, 2018; Crowther & Seifi, 2022). They also serve as a basis for reversing the World Economic Forum's findings on the behavior of many companies and organizations that often underestimate or overlook the environmental risks associated with their value chain and the lack of sustainable criteria in their projects and business activities (WEF, 2020).

In this sense, it is necessary, through ISO 14044 guidelines, to measure the impacts of CO_2 emissions from the traditional processes of the design of concrete mixtures on site that allow identifying

Table 1. LCA analysis models based on NTC-ISO 14044. Source: Preparation by the authors.

Region	Tool	Description
USA	TRACI (Tool for Reduction and Assessment of Chemical and Other Environmental Impacts) (Henderson, Niblick, & Golden, 2021)	This assesses environmental impacts and provides a database of environmental impacts that can be used in life cycle analysis.
	BEES (Building for Environmental and Economic Sustain-ability) (Kneifel et al., 2019)	This allows AECO actors to select cost-effective and environmentally friendly construction products based on consensus standards.
Spain	UNE-EN 15804:2012+A1:2014	This provides a framework for the product's envi-ronmental statement and evaluates its LCA based on buildings.
European Union	PEF (Product Environmental Footprint) (European Commission, 2021)	These evaluate the multi-criteria environmental impact of products and organizations. They follow the principles of ISO 14040 and 14044.
	OEF (Organizational Environmental Footprint) (Damiani et al., 2022)	
	EW-MFA (Material flow account) (Europäische Kommission Statistisches Amt, 2018)	Theoretical and conceptual foundations of the underlying statistical methodology.
Global	SimaPro (Speck et al., 2016)	LCA analysis software. This follows the ISO princi-ples.
	EIO-LCA (Azari, 2019)	This evaluates economic and environmental inter-connections on a national or regional scale.
	SFA (Substance Flow Analysis) (Chertow, 2004)	This evaluates the flow of substances in a given area for a given time (usually a year).

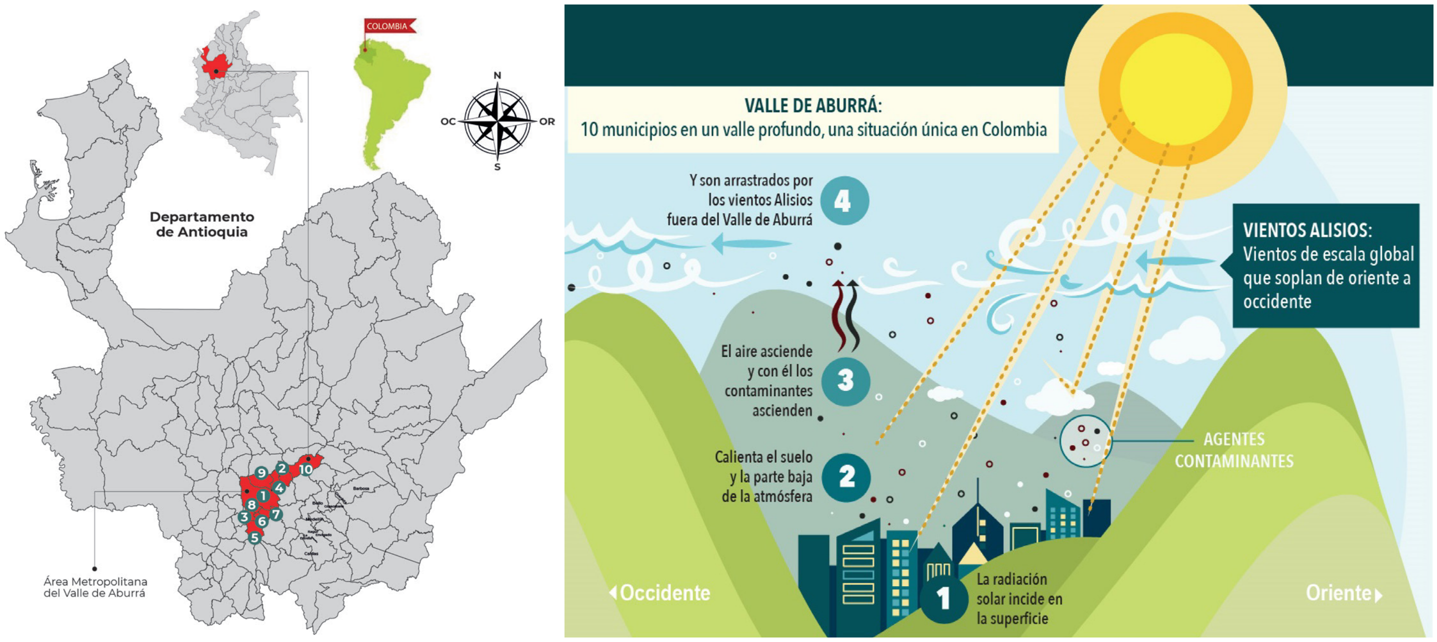

Figure 1. Scenario - Aburrá Valley. Source: Map (Asoareas, 2021), Image (SIATA, 2016).

strategies that contribute to the GHG mitigation challenges in the region so that these can align with public climate change policies. In this case, the city of Medellín – Colombia, has been chosen, taking as a reference the Climate Action Plan PAC 2020 -2050 (Mayor's Office of Medellín, 2020) for the metropolitan nucleus of the Aburrá Valley.

The current phase of the research collates a data survey associated with the properties of aggregates from different quarries across the Aburrá Valley Metropolitan area in the Antioquia department in Colombia. Given the topographic and climatological characteristics, this territory is defined as an atmospheric basin (AMVA, 2015), as mountains delimit its space, leading to the concentration and reaction of gases and air pollutant particles that are not entirely displaced by the winds (Figure 1).

The mountainous perimeter conditions the distribution generated by the trade winds system; therefore, the phenomenon worsens in some seasons. (Agusti-Panareda et al., 2019; B. Liu et al., 2023; SIATA, 2016). A local study (AMVA, 2017) indicates that this type of condition generates a concentration effect characterized by a low-altitude atmospheric limit and high cloud cover, limiting the penetration of solar radiation and causing air cooling. This added to the weak winds, limits the dispersion of particulate matter and other pollutants. This situation is exacerbated by a growing population density of 3557 inhabitants /km^2, which demands the construction of typical buildings, with an average of 30 floors, that use structural systems based on reinforced concrete walls. This results in an accelerated increase in concrete production and, consequently, in the exploitation of its raw materials.

In this scenario, pollution episodes are generated that are greatly accentuated by the load generated by the car fleet. The PAC 2020-2050 indicates that: "the proportion of contribution to pollution by industrial sources is close to 30%, while mobile sources generate about 69% of the atmospheric emissions evaluated and, in particular, are responsible for 91% of the PM 2.5 emissions" (Mayor's Office of Medellín, 2021). The impact of the vehicle fleet constitutes one of the fundamental GHG variables for the region, particularly for concrete production activities, as the intensive use of aggregates (sand/gravel) and their transport from the quarries implies a constant circulation of cargo vehicles needed for their on-site production.

The recognition and reflection on this situation in the environment should favor the development of a sustainable awareness in any economic activity linked to the construction value chain. One of the critical benefits of this lies in the educational processes, where awareness allows students to develop systemic thinking that leads them to evaluate the impact of their decision-making and the ability to manage carbon (CLC, 2016) through the acquisitions of resources throughout their life cycle (Bohvalovs et al., 2023; Martinsone et al., 2023). For the construction economic sector, this can represent progress towards the sustainable development of buildings and the dissemination of relevant information related to sustainability.

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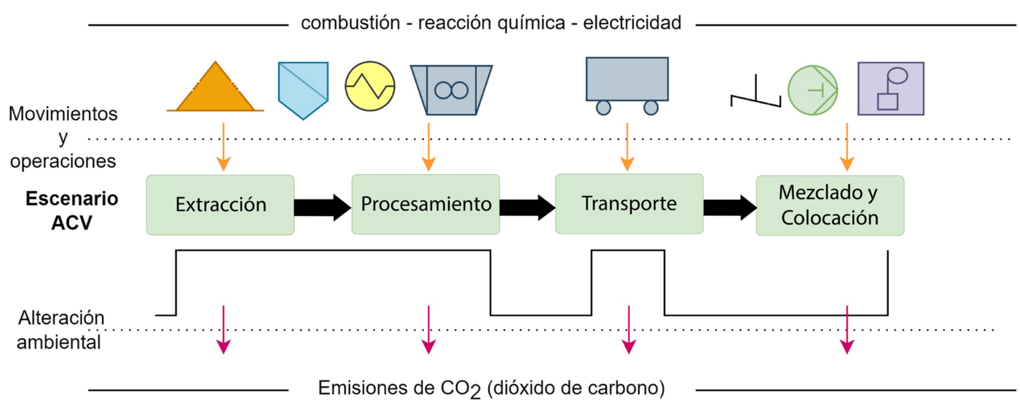

Figure 2. Holistic context of the concrete emission cycle. Source: Preparation by the authors.

CONCRETE AND ENVIRONMENT RELATIONSHIP

Concrete is the most used artificial material in the world, with more than 25 Gt/year (De Andrade Salgado & De Andrade Silva, 2022; Gursel et al., 2014). It comprises four essential ingredients: water, cement, gravel as coarse aggregate (CA), and sand as fine aggregate (FA). These raw materials constitute one of the most extracted mineral resources on the planet (Del Rey Castillo et al., 2020). In addition, this product includes stages in its energy-intensive manufacturing process and operations, which are responsible for much of the greenhouse gas emissions. The global cement industry produces 4.1 billion tons annually, accounting for 8-10% of anthropogenic CO_2 emissions globally (Poudyal & Adhikari, 2021; Vázquez-Calle et al., 2022). In addition, studies indicate that for every kilogram of cement produced, 0.80-0.90 kilograms of carbon dioxide are released into the environment, making cement production the leading GHG producer after electricity production plants (Ajayi & Babafemi, 2024). According to Duque (2020), a typical concrete with a strength of 25 MPa generates 0.29 t CO_2 —eq/m^3 and cement production represents 82% of this figure.

The significant increase in concrete use in recent decades, due to the increase in the world population and the corresponding demand for infrastructure, has caused a significant environmental problem (Youssf et al., 2024). Figure 2 presents a comprehensive view of the raw material's life cycle stages, from extraction to processing and site placement. Due to access restrictions, in this scenario, the research project involves only the characterization of coarse and fine aggregates from different sources to generate an inventory of this particular line. The details of this process are described in the methodology.

These resources are in high demand in Colombia, and the consumption trend is growing. The country's concrete production volumes reached a production of 6.9 million m^3 from June 2022 to June 2023, a growth of 3.7% compared to June 2022. 68.0% of the production was oriented to housing, 23.3% to civil works, and 18.6% to buildings. For the same period, the department of Antioquia region, comprising 123 municipalities, in which Medellín and its Metropolitan Area are located, showed the highest growth, with an increase of 17.6%, a dispatch of 179,855 tons of cement, and a total concrete production of 89,376 m^3 (DANE, 2023).

These statistics underline the importance of LCA in concrete production and monitoring the production and transport of inputs to develop data and prepare GHG projections associated with these volumes and how, from early stages, to interpret the impacts for the definition of mitigation strategies.

In Colombia, the design of concrete mixtures currently does not include tools or practices for quantifying the environmental impact associated with the generation of CO_2 and its impact on climate change because there are disjointed methodologies for this purpose. Based on computer solutions or tools such as Product Life Cycle Management or PLM (Product Life Management), the selection criteria for smarter supply chains can be favored and, therefore, contribute with technological means to the context of Industry 4.0 and, consequently, to the explicit implementation of public policies (Stegmann, 2020). These policies, aimed at the country's sustainable development, should encourage energy efficiency and promote sustainable construction practices. In this way, it aligns with the fulfillment of the Sustainable Development Goals (SDGs), which emphasize the creation of sustainable cities and communities and consumption and production patterns to reduce greenhouse gases (GHG) by 20%.

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Table 2. Approaches related to GHG mitigation and environmental impacts. Source: Preparation by the authors.

Approach	Framework	Technical	Source
Concrete Optimization	Optimization techniques	Predictive models AI - ML	(Zandifaez et al., 2023)
		Multi-objective optimization Inventory allocation	(Z. Liu et al., 2023)
	Selection of aggregates	Artificial aggregates	(Siamardi et al., 2023)
		Calcareous	(Jamil et al., 2023)
LCA	Life Cycle Assessment	Petrographic analysis	(Ghadir et al., 2021)
	Environmental Impact Assessment	Contraction/reduction Recycled materials	(Goyal et al., 2023)
		Comparative studies Decarbonization strategies	(Bush et al., 2022)

Table 3. Studies on optimization techniques to mitigate CO2 and GEI. Source: Preparation by the authors.

Source	Study	Optimization techniques	Sustainability Parameters
Naseri et al., 2023 North America-Oceania	A novel evolutionary learning to prepare sustainable concrete mixtures with supplementary cementitious materials	Evolutionary learning algorithms, optimization programming	Reduction of global warming potential, energy consumption, material consumption, embodied CO_2
Wang et al., 2022 Asia	Energy Optimization Design of Limestone Hybrid Concrete in Consideration of Stress Levels and Carbonation Resistance	Genetic algorithm, water cycle algorithm	Mechanical strength, carbonation resistance, environmental impact, embodied energy
Naseri et al., 2020 Asia-North America	Designing sustainable concrete mixture by developing a new machine-learning technique	Machine learning algorithms, statistical modeling	Reduction of embodied CO_2, energy consumption, material consumption
Khan, Do and Kim, 2016 Asia	Cost-effective optimal mix proportioning of high-strength self-compacting concrete using response surface methodology	Response surface methodology (RSM)	Costs, environmental impact, compressive strength, durability
Ibe et al., 2022 Africa	Optimization and Simulation of Saw Dust Ash Concrete Using Extreme Vertex Design Method	Extreme vertex design	Reduction of embodied CO_2, durability, mechanical properties
Ewa et al., 2023 Africa	Optimization of saw dust ash and quarry dust pervious concrete's compressive strength using Scheffe's simplex lattice method	Scheffe's simplex network method	Compressive strength, environmental impact, sustainability of materials
Kim et al., 2022 North America	OpenConcrete: a tool for estimating the environmental impacts of concrete production	Impact scenario analysis to produce a representative concrete mix in the United States	Emissions of GHG, nitrogen oxide, sulfur oxide, and volatile organic compounds, embedded energy, water consumption, and emissions of particles smaller than 2.5 microns (PM2.5).
Berkeley, n.d.	Green Concrete LCA Web Tool	Quantification of the environmental impacts of the production of concrete and its components (such as cement, aggregates, additives, and supplementary cementitious materials).	GHG emissions, embedded energy.

The most recent studies address combined frameworks and explore properties of traditional materials and new additions, looking for efficiencies and optimizations that contribute to lower consumption rates of cementing material (Portland cement) and a lower carbon footprint (Table 2).

From the point of view of environmental protection, these investigations are associated with sustainable design and contribute to the mitigation of impacts. This work is framed in the same line as the optimization and efficient concrete dosing to promote best practices and value criteria that reduce the effects generated by human activity around

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construction as proposed (Oladazimi et al., 2020). Although the efforts are not yet integrated and the environmental challenges of cement and concrete production persist (Belaïd, 2022b), research processes and analytical models based on ISO 14044 continue to contribute to knowledge in order to approximate standardized criteria for advanced decision-making. Table 3 records specific studies aimed at GHG optimization and mitigation. In addition, it has been observed that the computer tools developed allow quantifying the environmental impacts associated with concrete mixtures. However, these tools have limitations because they do not integrate phases such as the mixtures' design depending on the materials' properties specific to the place and the use of established cement contents.

In addition, these studies usually focus only on quantifying greenhouse gases and embedded energy. However, the effect that variables such as the percentage of moisture, aggregate sizes, and other physical properties of materials may have is not clearly evident. Due to their stochastic nature, these variables can influence the results of the developed tools.

Therefore, this study focuses on applying Life Cycle Analysis (LCA) to the design of concrete mixtures in the Metropolitan Area of the Aburrá Valley, Colombia. Its purpose is to demonstrate that the identification, characterization, correct choice, and optimization of the proportions of concrete mixtures can reduce CO_2 emissions, energy consumption, and other environmental impacts. This is especially relevant in a highly informal sector in Colombia, where there are gaps in the objective criteria for defining the sources of raw materials for producing concrete mixtures. In addition, the lack of a selection with environmental criteria from the methodological point of view hinders an agile response to the execution of infrastructure works. This study seeks to raise awareness and guide decision-makers in the execution and design of construction processes by selecting the raw materials used to manufacture concrete mixtures in different buildings. To contribute to the solution, a methodology is proposed that, based on the identification of the sources, the characterization of the materials and their environmental statement, together with the articulation of concrete mixture design techniques, can generate environmental and economic benefits in the production of concrete, in addition to highlighting the need for the construction sector to implement this type of practices and initiatives.

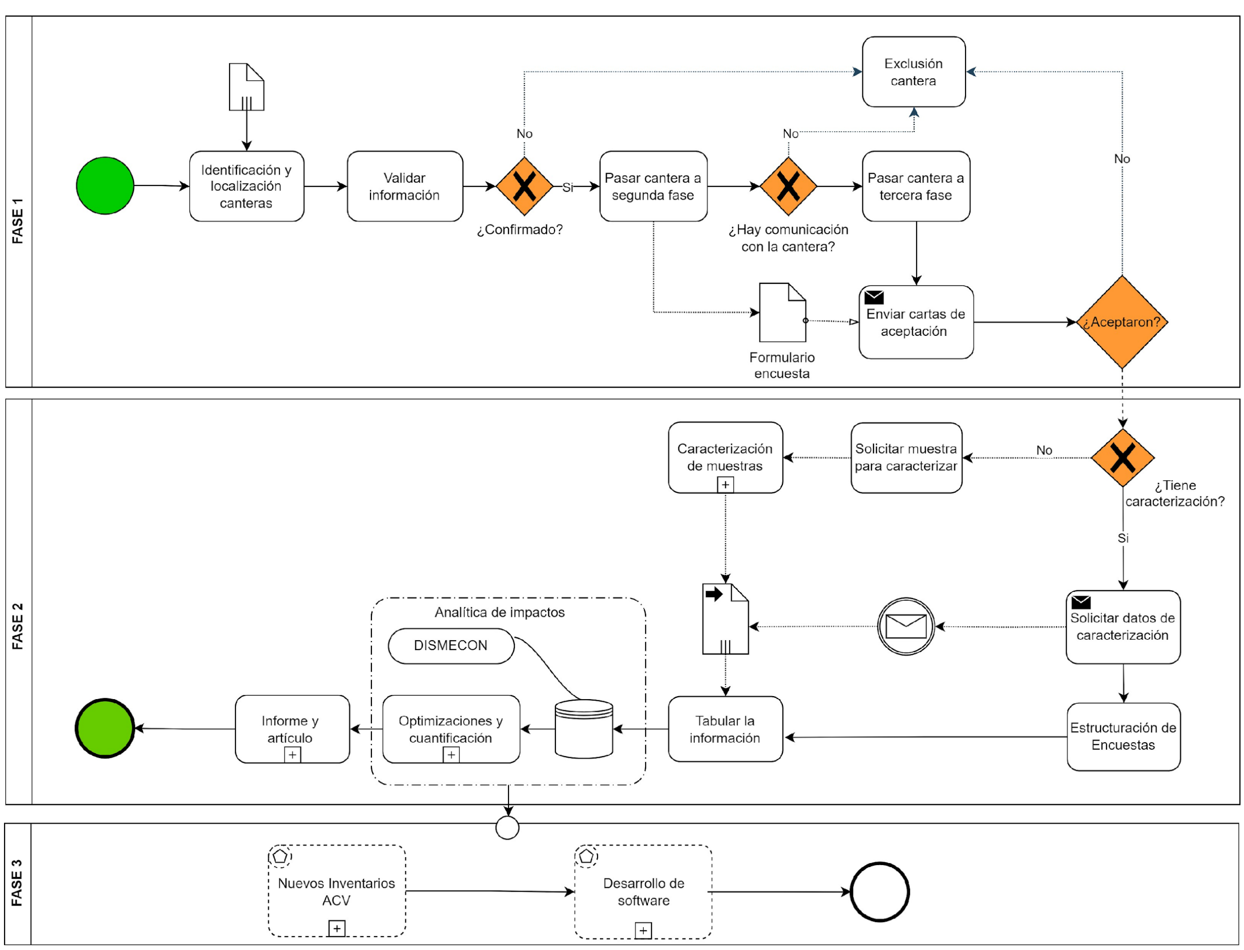

Figure 3. Phases of the methodological process. Source: Preparation by the authors.

METHODOLOGY

This research considers three phases framed in the LCA. In its first and second phases, the on-site concrete production scenario is contemplated and focuses on aggregate management as the first inventory for evaluating GHG emissions and their relationship with the design of mixtures. The inventories associated with ready-mixed concrete (production in industrialized plants) are not addressed in this article; this is proposed for a future phase 3.

Data of the characterization of the materials produced in quarries (n=13) located in the Metropolitan Area of the Aburrá Valley, Table 2, are used to determine the dosages of optimal concrete mixtures from the economic and environmental point of view. Figure 3 presents the proposed methodological process, highlighting the first two phases, the progress of the current research, and the stage 3 scenario where the development of a GHG estimation software for concrete in situ and premixed will be addressed.

Figures 4 and 5 show the characterization of the quarry materials, fine and coarse aggregates, under normative parameters (Colombian NTC Technical Standards and their equivalents to ASTM standards). Table 4 identifies the distribution of raw material sources in the 10 municipalities of the Metropolitan Area of the Aburrá Valley for a total of 13 quarries between fine and coarse aggregates.

Figure 4. Protocols conducted to determine the different normative tests and data sources comprising the characterization of the coarse aggregates (CA).

The data obtained through the characterization tests allow the parameterization of their properties based on the water-cement-aggregate ratio to ensure the required strength. Concrete quality depends on several factors; however, the design and the choice of raw materials, such as aggregates, are critical elements in its durability (Uthaman & Vishwakarma, 2023).

ENVIRONMENTAL INVENTORY OF MATERIALS

The impact analysis used the theoretical framework that analyzes the processes related to concrete production in the Metropolitan Area of the Aburrá Valley. The database was consulted for the inventory of the environmental statement of the concrete mixtures' materials (*THE INTERNATIONAL EPD SYSTEM*, 2024), seeking the companies supplying Portland cement and fine and coarse aggregates from the geographical place under study. Only two companies were identified: Argos Cement

Table 4. Location of sources of aggregates. Source: Preparation by the authors.

Municipality	Number of Quarries Evaluated
Medellín (Dtto.)	4
Girardota	3
Caldas	3
Itagüí	1
Bello	2

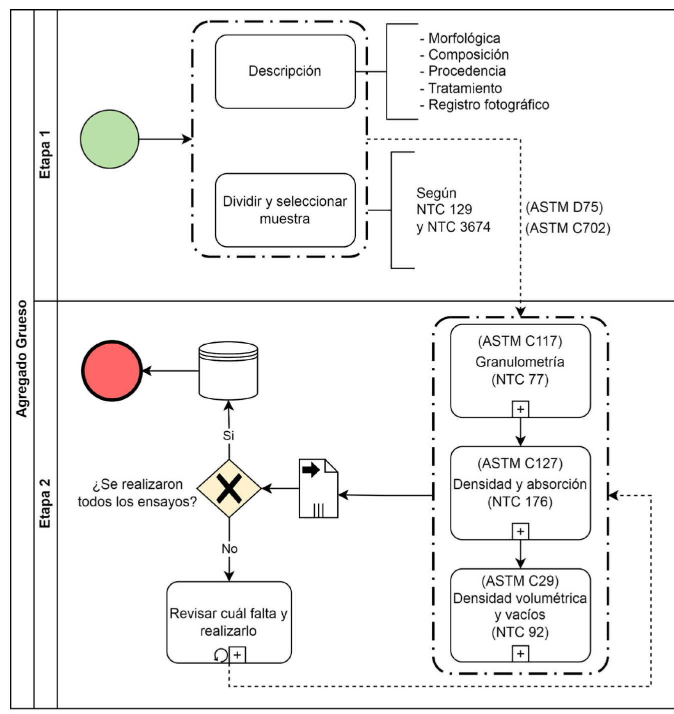

Figure 4. Methodological process of CA characterization. Source: Preparation by the authors.

(Portland Cement Association, 2014) for cement and (Industrial Conconcreto S.A.S., 2019) for fine and coarse aggregates

To make an environmental inventory of the materials, the following environmental hypothesis is proposed: *"Respectively, the fine aggregate and coarse aggregate materials of the Metropolitan Area of the Aburrá Valley, due to their geology and form of extraction, present an identical EPD (Environmental Product Declaration) to those reported by Industrial Conconcreto."*

The declared functional unit is one metric ton for fine and coarse aggregates, specifically sand for concrete and coarse aggregate, with nominal maximum sizes of 19 mm and 25 mm. The indicators are presented in Table 5.

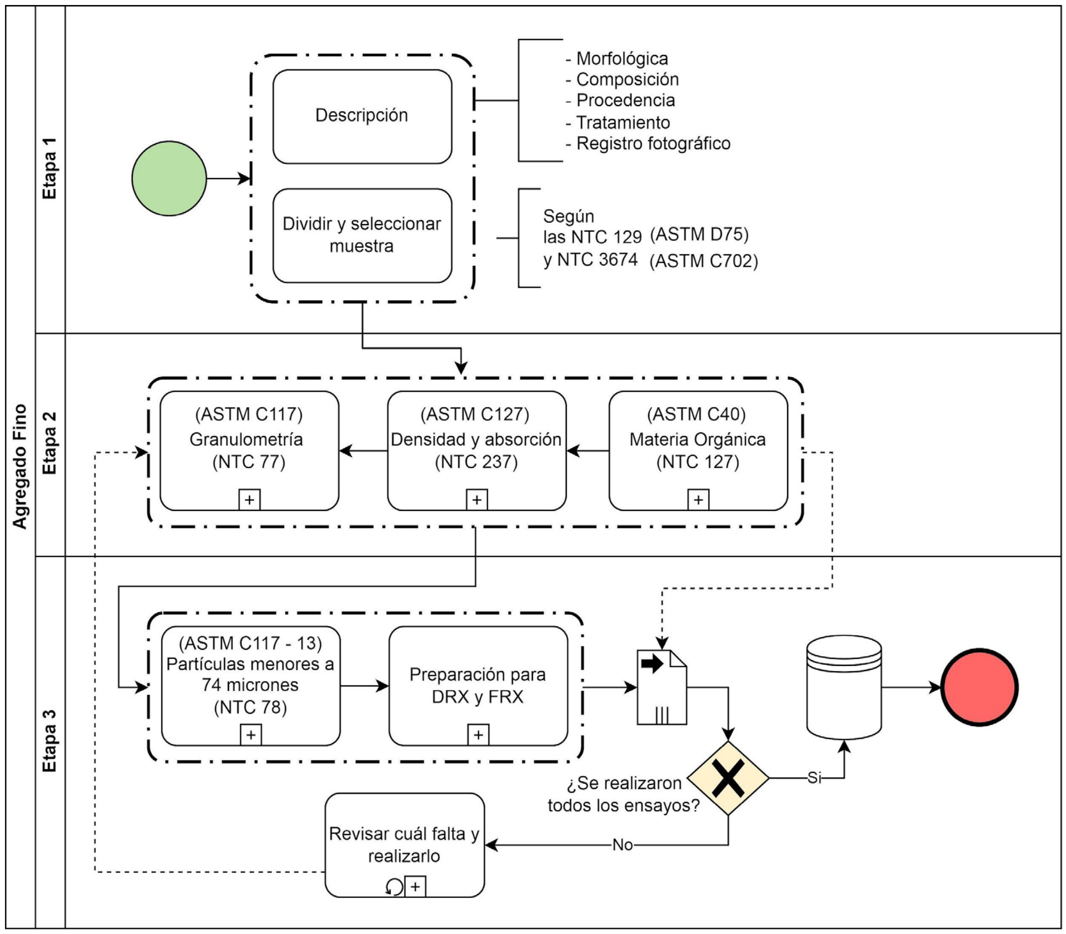

Figure 5. Methodological process of FA characterization. Source: Preparation by the authors.

Table 5. Environmental impact indicators cement and aggregates. Source: Adapted from Industrial Conconcreto S.A.S. (2019) and Portland Cement Association (2014).

Indicator	Indicator Abbreviation	Unit	Fine Aggregate	Coarse aggregate	Cement
Global Warming Potential (100 years)	IA1	kg CO_2-eq	3.34	2.70	892.00
Marine eutrophication potential	IA2	kg N-eq	0.013	0.010	1.100
Freshwater phosphate ions' eutrophication potential	IA3	kg PO_4^{3-}- eq.	0.006	0.004	0.000
Freshwater eutrophication potential	IA4	kg P-eq.	0.00032	0.00025	0.00000
Eutrophication potential, accumulated excess	IA5	mol N-eq.	0.130	0.107	0.000
Non-renewable Primary Energy: Fossil	IA6	MJ	56.75	42.76	4660.00
Renewable Primary Energy: Solar, Wind, Hydro-electric, Geothermal	IA7	MJ	6.91	6.27	95.50
Total embedded energy	IA8	MJ	63.66	49.02	5243.40
Non-renewable Material Resources	IA9	kg	0	0	1240
Renewable Material Resources	IA10	kg	0	0	3.42
Net Freshwater	IA11	m^3	301.70	145.50	9240.00
Non-hazardous Waste Generated	IA12	kg	111.30	51.50	10.50
Hazardous Waste Generated	IA13	kg	0.0012	0.0011	0.0511

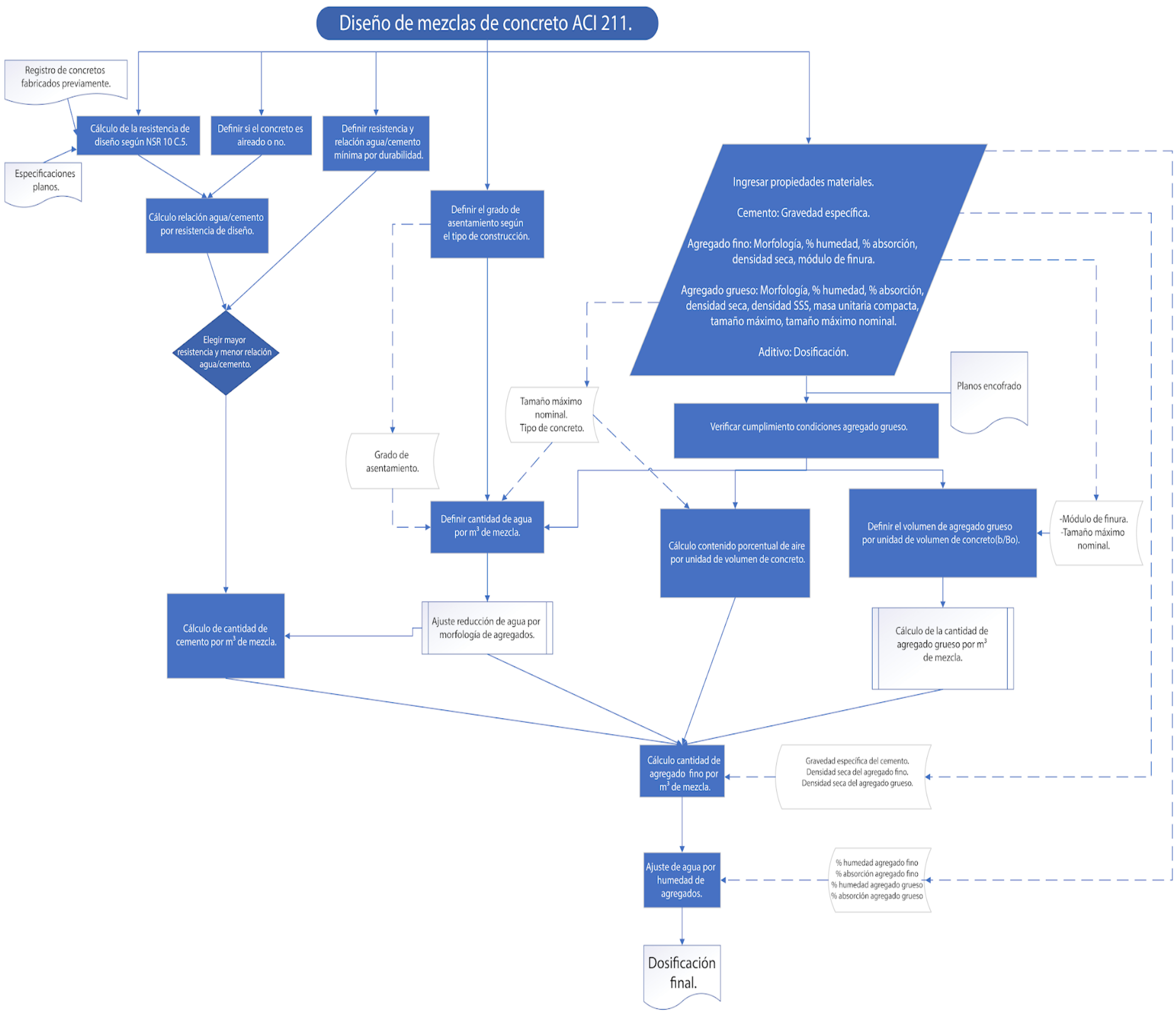

Figure 6. Operation framework - DISMECON software. Source: Preparation by the authors.

ENVIRONMENTAL QUANTIFICATION AND OPTIMIZATION OF CONCRETE MIXTURES.

The materials' environmental characterization data were tabulated and placed in the DISMECON base software (Restrepo et al., 2020). This tool can be used to estimate or approximate the initial quantities of materials for the design of mixtures. The software is based on the A.C.I 211 methodology (American Concrete Institute). It calculates the dosage of the materials according to the performance conditions (compressive strength, durability, workability) required of the concrete, from the physical properties of the aggregates such as density, unit weight, nominal maximum size, fineness modulus, density and absorption, among others (Table 5 and Table 6), and data of the mixtures such as the desired consistency, the application of the concrete, laying and formwork conditions, the exposure conditions, the w/c ratio, or the resistance. The software's operation can be seen in Figure 6.

The computer tool is modified in its programming to include the structured data and process the indicators of the environmental inventories obtained in Table 5. With this structure, the framework proposed by NTC-ISO 14044 is configured as follows: a) Objective and scope, b) Analysis of the life cycle inventory, c) evaluation of the life cycle impact, and d) interpretation.

Regarding the optimization scenarios, an optimization plan is designed based on the aggregates (FA/CA). To do this, 8 fine aggregates (Table 6) and 4 coarse aggregates (Table 7) were evaluated. To establish a baseline in the simulation of concrete mix designs, a structural concrete of the lowest possible resistance is considered according to the 2010 earthquake-resistant standard (NSR) and the lowest settlement contemplated in the concrete mix design methodology. These parameters generate the scenario of less cement demand for this type of concrete and, consequently, the lowest environmental loads. The design parameters have the following configuration:

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Table 6. Ratios of FA types - Optimization for application. Source: Preparation by the authors.

Fine Aggregate (FA)	Fineness Modulus [ASTM C117]	Dry Bulk Density (kg/m3) [ASTM C127]	Absorption (%) [ASTM C127]	Morphology
1F	3.00	2709	1.90	Crushed
2F	3.76	2620	0.87	Crushed
3F	2.70	2901	1.03	Crushed
4F	3.01	2602	2.40	Crushed
5F	3.00	2646	1.98	Crushed
6F	3.14	2550	1.21	Crushed
7F	4.00	2750	1.07	Crushed
8F	3.40	2786	0.99	Crushed

Table 7. Ratios of CA types - optimization for application. Source: Preparation by the authors.

Coarse Aggregate (CA)	Max size (mm) [ASTM C117]	Nominal maximum size (mm) [ASTM C117]	Dry bulk density (kg/m3) [ASTM C127]	Compact unit mass (kg/m3) [ASTM C29]	Absorption (%) [ASTM C127]	Morphology
1C	50.0	37.5	2863	1499	0.24	Crushed
2C	37.5	25.0	2735	1635	1.50	Crushed
3C	25.0	19.0	2770	1610	0.86	Crushed
4C	25.0	19.0	2862	1707	0.92	Crushed

TYPE OF CONVENTIONAL CONCRETE

- Non-aerated concrete.
- Design resistance 21 MPa.
- Type of construction: Mass concrete.
- Settling: 50 mm.

The analysis of the additives that modify the properties in the plastic state is not included because the case study represents a concrete mixture with easily achievable mechanical characteristics. Additionally, the impacts reported by the European Federation of Concrete Admixtures Associations Ltd (EFCA, 2015) only include the energy demands and not the environmental loads associated with the chemical processes of the additives, thus limiting the scope.

RESULTS AND DISCUSSION

CHARACTERIZATION OF AGGREGATES

The results of the characterization of the aggregates from the quarries evaluated in the Metropolitan Area of the Aburrá Valley show variations in physical properties with some atypical data that may be associated with changes in production processes.

For the fine aggregates, it is observed in Figure 7 that the average value of the absorption percentage is 1.63%, which is in line with the ACI 211 methodology, which establishes 2% as the maximum absorption of the aggregates. On the other hand, about 29% of the data has absorption values greater than 2%. Additionally, the humidity percentages vary between 0% -8%. This range of values is accepted to prepare concrete. The fineness moduli obtained between 2.8 and 3.2 are ideal values for the sand used to manufacture concrete. However, 50% of the aggregates have a Fineness Modulus (FM) between 3.6 and 4.3, values associated with arenon, characteristic of very coarse sands that can induce very rough and unmanageable concrete mixtures. Finally, the Dry Bulk Density (DBD) has values around 2100 kg/m^3 and 2900 kg/m^3.

Similarly, it is observed from Figure 8 that

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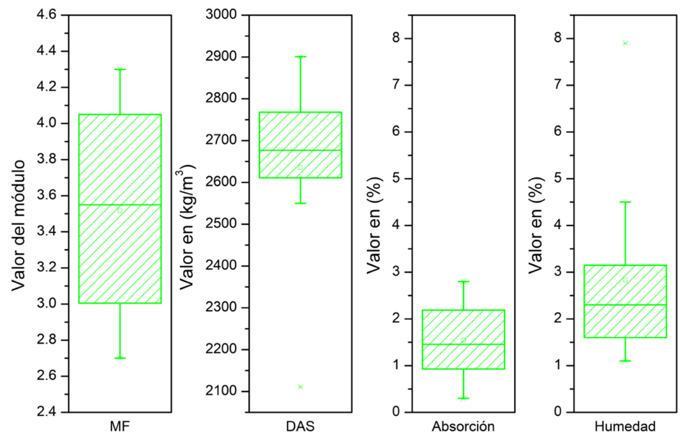

Figure 7. Characterization properties of Fine Aggregates. Source: Preparation by the authors.

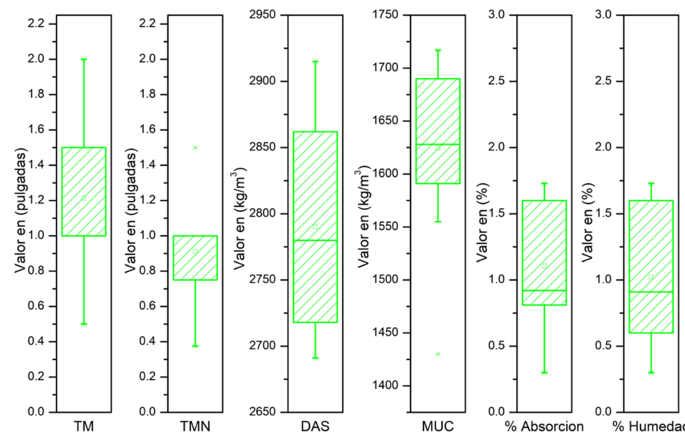

Figure 8. Characterization properties of Coarse Aggregates. Source: Preparation by the authors.

approximately 100% of the coarse aggregates have absorption percentages lower than 2%, qualifying them as suitable for use. The Maximum Size (MS) and Nominal Maximum Size (NMS) account for the tendency (75%) to produce thick aggregates with sizes between 1½" (38 mm) and 2" (50.8 mm) due to the need to meet, in steel-reinforced concrete construction systems, the geometric requirements of the formwork and the distances between the rebars. The Compact Unit Mass (CUM) was located between 1425 kg/m^3 and 1720 kg/m^3, and the humidity percentage was between 0% and 1.8%, the latter in the range of accepted values for concrete preparation. When comparing Figure 7 and Figure 8, a higher average Dry Bulk Density (DBD) is observed for coarse aggregates (2790 kg/m^3) than fine aggregates (2628 kg/m^3), which is associated with the number of voids between the fine aggregate particles, requiring in these cases a greater amount of mortar paste to achieve adequate workability of the mixture (Pérez et al., 2022).

DESIGN OF MIXTURES

Under the specified conditions and raw materials, the concrete design resulted in 32 possible dosages detailed in Table 8. 3 trends in cement consumption were identified (266 kg, 290 kg, 316 kg), which are related to the maximum size of coarse aggregate. This implies a reduction of up to 15.8% in the demand for cement when comparing the maximum and minimum values and an increase in aggregate consumption of up to 7.2%. In addition, an increase in water consumption of up to 15.7% is observed when comparing the average water consumption between the mixtures with the highest and lowest demand for cement. When considering the cost and the high environmental impact of cement, these findings suggest the importance of more informed decision-making by project developers to optimize both the cost and the environmental impact of the concrete mixtures to be produced.

Table 8. Dosages of concrete mixtures. Source: Preparation by the authors.

Mix ID	Mix	Concrete Dosage				Quantities x 1 m3 of Concrete						
		Cement (parts)	Fine Aggregate (parts)	Coarse Aggregate (parts)	Water/ cement ratio	Cement (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Total aggregates (kg)	Average Aggregate Total (kg)	Water (L)	Average Water (L)
1	3F1C	1	4.408	4.057	0.555	266	1172.6	1079.3	147.7	2165.1	157.1	152.8
2	8F1C	1	4.618	3.663	0.555	266	1228.3	974.4	147.5		145.7	
3	7F1C	1	4.883	3.325	0.56	266	1298.8	884.4	149		147.7	
4	1F1C	1	4.277	3.888	0.591	266	1137.6	1034.3	157.1		161.7	
5	5F1C	1	3.646	4.463	0.62	266	969.8	1187.2	164.9		164.9	
6	4F1C	1	4.113	3.883	0.608	266	1094	1032.8	161.7		148.6	
7	2F1C	1	4.528	3.46	0.548	266	1204.5	920.4	145.7		149	
8	6F1C	1	4.096	3.809	0.559	266	1089.5	1013.3	148.6		147.5	

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Mix ID	Mix	Concrete Dosage				Quantities x 1 m3 of Concrete						
		Cement (parts)	Fine Aggregate (parts)	Coarse Aggregate (parts)	Water/ cement ratio	Cement (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Total aggregates (kg)	Average Aggregate Total (kg)	Water (L)	Average Water (L)
9	3F2C	1	3.451	3.834	0.593	290	1000.7	1111.8	172	2040.0	179.6	174.6
10	8F2C	1	3.716	3.439	0.588	290	1077.6	997.4	170.6		168.4	
11	7F2C	1	4.008	3.101	0.589	290	1162.3	899.3	170.9		172	
12	1F2C	1	3.39	3.665	0.619	290	983	1062.8	179.6		183.6	
13	5F2C	1	3.311	3.665	0.621	290	960.2	1062.8	180		180	
14	4F2C	1	3.261	3.659	0.633	290	945.8	1061.1	183.6		172.1	
15	2F2C	1	3.689	3.24	0.581	290	1069.8	939.5	168.4		170.9	
16	6F2C	1	3.264	3.586	0.593	290	946.7	1039.9	172.1		170.6	
17	3F4C	1	3.253	3.403	0.565	316	1027.9	1075.4	178.5	2008.9	185.9	181.3
18	3F3C	1	3.341	3.21	0.562	316	1055.7	1014.3	177.6		175	
19	8F4C	1	3.492	3.025	0.562	316	1103.4	955.9	177.7		177.6	
20	1F4C	1	3.191	3.241	0.59	316	1008.3	1024.2	186.6		190.1	
21	7F4C	1	3.758	2.701	0.565	316	1187.6	853.5	178.6		186.2	
22	8F3C	1	3.567	2.872	0.56	316	1127.2	907.6	176.9		178.1	
23	5F4C	1	3.117	3.241	0.592	316	984.9	1024.2	186.9		177.9	
24	7F3C	1	3.824	2.547	0.563	316	1208.5	805	177.9		176.9	
25	1F3C	1	3.269	3.057	0.588	316	1033	966	185.9		186.6	
26	4F4C	1	3.07	3.236	0.603	316	970	1022.5	190.7		175.8	
27	2F4C	1	3.462	2.831	0.556	316	1093.9	894.5	175.8		178.5	
28	5F3C	1	3.193	3.057	0.589	316	1009	966	186.2		190.7	
29	6F4C	1	3.071	3.166	0.566	316	970.4	1000.3	178.9		186.9	
30	4F3C	1	3.145	3.052	0.602	316	993.7	964.4	190.1		178.9	
31	2F3C	1	3.528	2.67	0.554	316	1114.8	843.6	175		178.6	
32	6F3C	1	3.143	2.986	0.564	316	993.1	943.5	178.1		177.7	

Figure 9 illustrates the behavior of the material consumption of the different dosages for a concrete of 21 MPa from Table 8. There is evidence of a reduction in the average water demand of up to 15.7% due to a decrease in cement consumption from these. Additionally, mixtures with the same cement consumption can be optimized by reducing the average aggregate consumption by up to 6.6%. Thus, it is evident that the correct choice and combination of materials to make concrete mixtures can generate economies and their respective benefits without requiring major efforts.

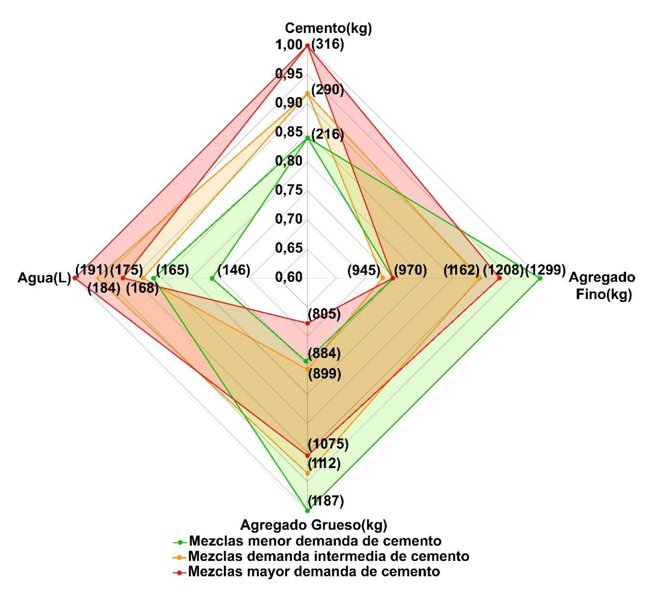

Figure 9. Relationship of consumption of materials of different mixtures for the same resistance target 21 MPa. Source: Preparation by the authors.

ECONOMIC QUANTIFICATION

The cost per cubic meter of each concrete mixing ratio of 21 MPa was calculated using the unit values expressed in USD/kg of the raw materials used in each mixture. As of March 2024, the commercial values of primary inputs in Colombia

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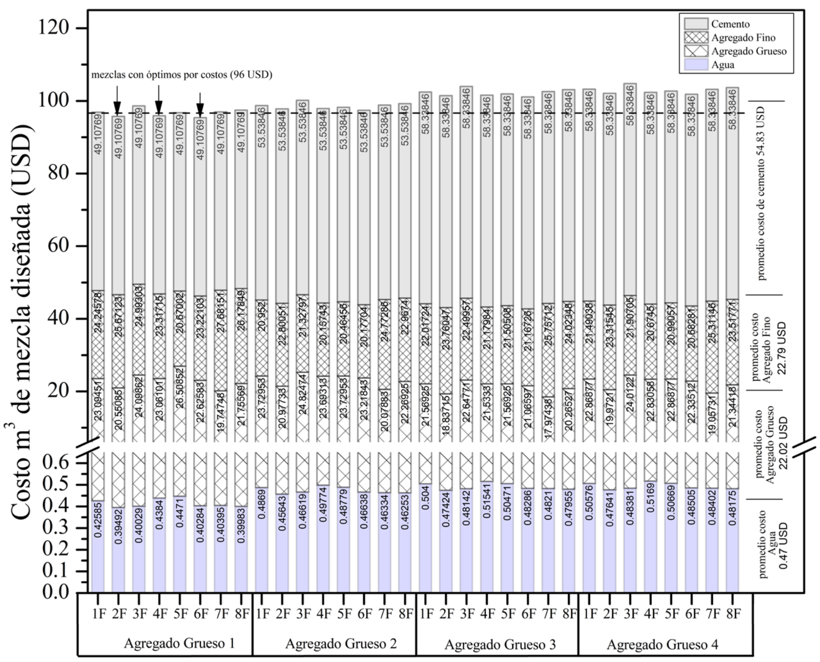

Figure 10. Cost of concrete mixtures. Source: Preparation by the authors.

were converted by an equivalence factor of 3900 Colombian pesos per American dollar. When analyzing the economic efficiency of the different proposed concrete mixtures, as seen in Figure 10, the raw material cost for 1 m³ of concrete varies between 95.36 USD and 104.74 USD, representing an economic optimization of up to 9%. It is evident that this reduction is directly associated with the decrease in the demand for cement, which is the most expensive component. In addition, it is observed that the 6F1C mixture, which has the lowest cost, achieves a balance in aggregate costs and has the lowest consumption among mixtures that share the same cement consumption index.

ENVIRONMENTAL QUANTIFICATION

The mixture with the lowest production cost (6F1C) primarily exhibits lower environmental impacts regarding CO_2- eq emissions, O_3-eq, embedded energy, and freshwater consumption. This is evidenced in Figure 11, built by evaluating the environmental impacts of the 32 designed mixtures and using the environmental inventory of the materials (cement and aggregates). In contrast, given the increase in the demand for aggregates in this mixture and the production process, the analysis shows higher levels of water pollution in lakes, ponds, rivers, and reservoirs, registering more significant impacts in terms of eutrophication and generation of non-hazardous waste.

Figure 12 quantifies the environmental impacts

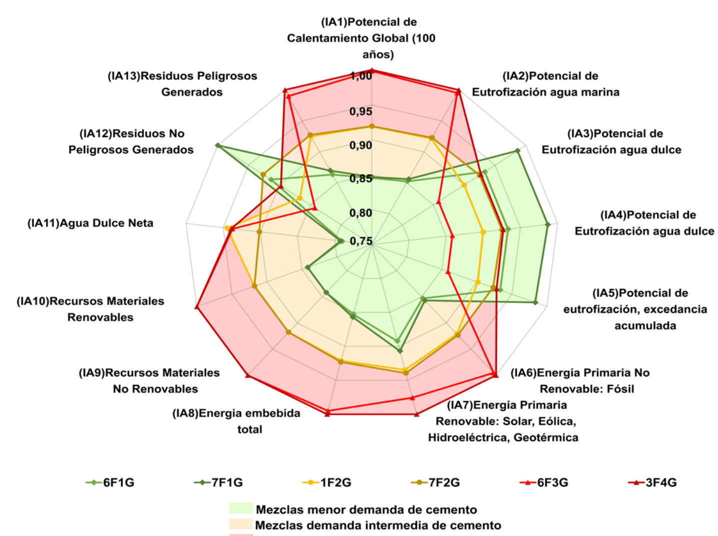

Figure 11. Relationship environmental impacts concrete mixtures. Source: Preparation by the authors.

associated with the production of 1 m³ of concrete according to the specifications of the proposed conventional concrete type (21 MPa). CO_2-eq emissions are highlighted, which range between 243.7 kg and 288.2 kg; total embedded energy, varying from 1513.8 MJ to 1775.1 MJ; and freshwater consumption, between 156.8 L and 200 L. These values suggest the possibility of achieving 15.4% reductions in CO_2 emissions, 14.7% in embedded energy, and 21.5 % in freshwater consumption.

Mezcla	IA 1		IA 2	IA 3	IA 4	IA 5	IA 6	IA 7	IA 8		IA 9	IA 10	IA 11	IA 12	IA 13
	kg CO2-eq	Promedio kg CO2-eq	kg N-eq	kg PO43- eq.	kg P eq.	mol N eq.	MJ	MJ	MJ	Promedio MJ	kg	kg	L	kg	kg
1F1G	243,9		0,320	0,0109	0,0006	0,3	1348,3	39,7	1517,9		329,8	0,9	166,8	182,7	0,016
2F1G	243,8		0,320	0,0108	0,0006	0,3	1347,3	39,5	1516,5		329,8	0,9	155,4	184,2	0,016
3F1G	244,1		0,321	0,0113	0,0006	0,3	1352,3	40,3	1522,3		329,8	0,9	157,4	188,9	0,016
4F1G	243,7	243,9	0,319	0,0107	0,0006	0,3	1345,8	39,4	1515,0	1517,7	329,8	0,9	171,4	177,7	0,016
5F1G	243,7		0,319	0,0107	0,0006	0,3	1345,4	39,5	1514,7		329,8	0,9	174,6	171,9	0,016
6F1G	243,7		0,319	0,0106	0,0006	0,3	1344,7	39,3	1513,8		329,8	0,9	158,3	176,2	0,016
7F1G	244,0		0,321	0,0112	0,0006	0,3	1351,1	39,9	1520,8		329,8	0,9	158,7	192,9	0,016
8F1G	244,0		0,321	0,0112	0,0006	0,3	1350,9	40,0	1520,7		329,8	0,9	157,2	189,7	0,016
1F2G	264,8		0,345	0,0102	0,0006	0,2	1452,6	41,1	1635,3		359,6	1,0	189,3	167,2	0,017
2F2G	264,8		0,345	0,0101	0,0006	0,2	1452,3	41,0	1634,7		359,6	1,0	178,1	170,5	0,017
3F2G	265,0		0,346	0,0105	0,0006	0,2	1455,7	41,6	1638,8		359,6	1,0	181,7	171,7	0,017
4F2G	264,7	264,8	0,345	0,0100	0,0006	0,2	1450,4	40,9	1632,8	1635,5	359,6	1,0	193,3	163,0	0,017
5F2G	264,8		0,345	0,0101	0,0006	0,2	1451,3	41,0	1633,8		359,6	1,0	189,6	164,6	0,017
6F2G	264,7		0,344	0,0099	0,0006	0,2	1449,6	40,8	1631,8		359,6	1,0	181,7	162,0	0,017
7F2G	265,0		0,346	0,0105	0,0006	0,2	1455,8	41,4	1638,7		359,6	1,0	180,6	178,7	0,017
8F2G	265,0		0,346	0,0104	0,0006	0,2	1455,2	41,4	1638,1		359,6	1,0	180,3	174,3	0,017
1F3G	287,9		0,374	0,0100	0,0006	0,2	1572,5	43,4	1770,0		391,8	1,1	195,6	168,0	0,019
2F3G	287,9		0,373	0,0100	0,0006	0,2	1571,9	43,2	1769,2		391,8	1,1	184,6	170,8	0,018
3F3G	288,1		0,374	0,0104	0,0006	0,2	1575,8	43,8	1773,8		391,8	1,1	187,3	173,0	0,019
4F3G	287,8		0,373	0,0098	0,0006	0,2	1570,2	43,1	1767,5		391,8	1,1	199,8	163,6	0,018
5F3G	287,9		0,373	0,0099	0,0006	0,2	1571,1	43,2	1768,5		391,8	1,1	195,9	165,4	0,018
6F3G	287,7		0,373	0,0097	0,0006	0,2	1569,3	43,0	1766,4		391,8	1,1	187,8	162,4	0,018
7F3G	288,1		0,374	0,0103	0,0006	0,2	1575,6	43,6	1773,3		391,8	1,1	187,5	179,3	0,019
8F3G	288,1	288,0	0,374	0,0103	0,0006	0,2	1575,3	43,7	1773,2	1770,8	391,8	1,1	186,6	175,5	0,019
1F4G	288,0		0,374	0,0102	0,0006	0,2	1573,6	43,6	1771,3		391,8	1,1	196,3	168,3	0,019
2F4G	287,9		0,374	0,0101	0,0006	0,2	1572,9	43,3	1770,4		391,8	1,1	185,4	171,1	0,019
3F4G	288,2		0,375	0,0105	0,0006	0,2	1576,9	44,0	1775,1		391,8	1,1	188,2	173,1	0,019
4F4G	287,9		0,373	0,0099	0,0006	0,2	1571,3	43,3	1768,8		391,8	1,1	200,4	163,9	0,018
5F4G	287,9		0,374	0,0100	0,0006	0,2	1572,2	43,4	1769,8		391,8	1,1	196,6	165,7	0,019
6F4G	287,8		0,373	0,0098	0,0006	0,2	1570,4	43,2	1767,7		391,8	1,1	188,6	162,8	0,018
7F4G	288,1		0,374	0,0104	0,0006	0,2	1576,4	43,7	1774,4		391,8	1,1	188,2	179,4	0,019
8F4G	288,1		0,374	0,0104	0,0006	0,2	1576,0	43,8	1774,0		391,8	1,1	187,4	175,4	0,019

Escala impactos: Mayor

Figure 12. Quantification of environmental impacts in concrete mixtures. Source: Preparation by the authors.

Figure 13 also shows the relationship between the decrease in the production cost of concrete mixing and the decrease in CO_2 emissions, embedded energy, and freshwater. Additionally, the eco-indicator values were determined based on the production cost regarding the categories of Global Warming Potential impact and Total Embedded Energy, as evidenced in Figure 14, where the best performance in the mixtures are precisely the most economical and those that require less Portland cement to achieve the same mechanical resistance. This shows, not only by environmental factors but also by economic factors, the benefit of this type of initiative when choosing aggregates to manufacture concrete on the worksite. Although this work establishes a methodology that shows a quantification of environmental impacts to apply to concrete mixtures designed for 21 MPa, it is possible to use it in different strengths and specifications, establishing environmental impact indicators that are more consistent with the local reality and whose potential use can be scaled to other latitudes that have an environmental product declaration (EPD) for materials and use the A.C.I methodology to design concrete mixtures.

Taking into account that only in 2023 about 89376 m^3 of ready-mixed concrete were produced in the Metropolitan Area of the Aburrá Valley (DANE, 2023), if this amount of concrete is optimized using the methodology used, comparing the most unfavorable case with the most favorable, an estimated saving of about US $838,346.88 could be achieved. In addition, emissions of approximately 3977 tons of CO_2 could be avoided, 23354 GJ of energy saved, and 4022 tons of freshwater

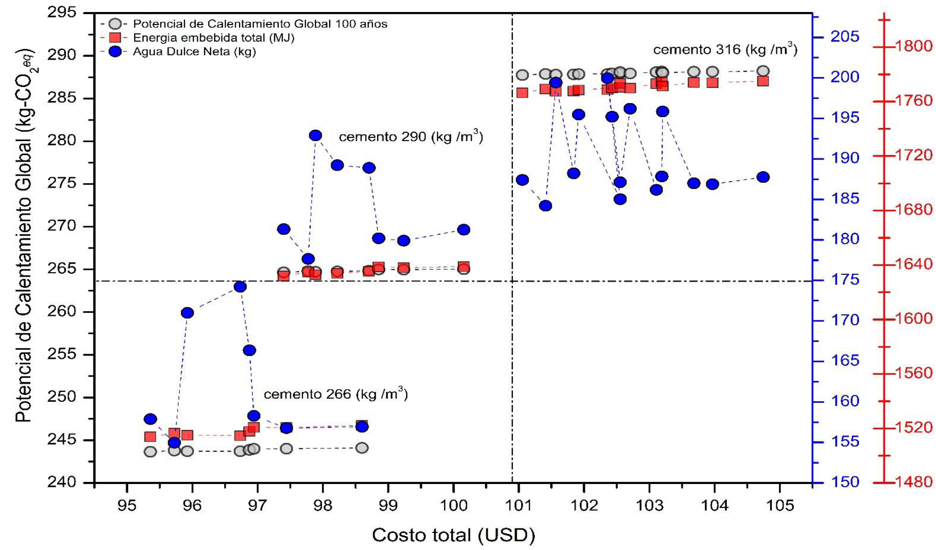

Figure 13. Cost-environmental impact ratio in concrete mixtures of 21 MPa. Source: Preparation by the authors.

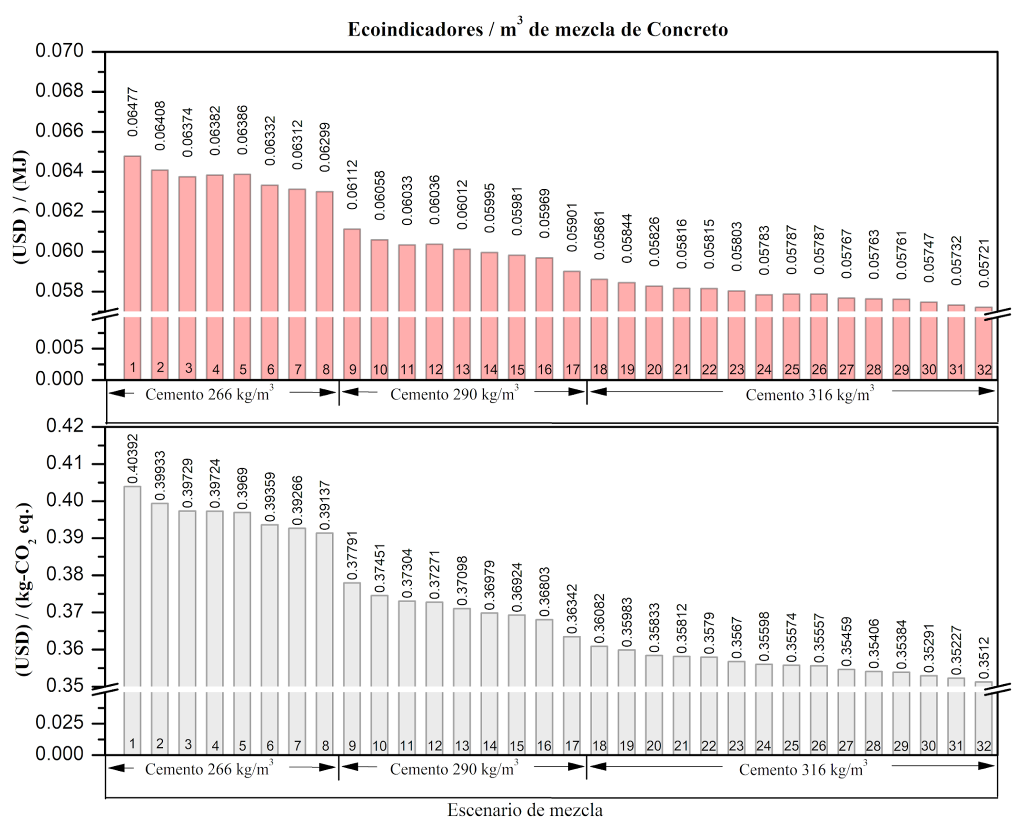

Figure 14. Graph eco-efficiency concrete mixtures of 21 MPa. Source: Preparation by the authors.

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conserved. This approach would not only benefit the construction sector but also provide an alternative route to mitigate the environmental impacts associated with this industry.

DISCUSSION

The research shows the possibility of economically and environmentally quantifying and optimizing some production processes in the construction industry. To achieve this, the integration of all the actors involved is required. This includes raw material producers, their level of formalization, and the adoption of best practices, such as environmental declarations of their products (EPD)- similarly, the transport companies and the characteristics of their fleet. Likewise, the architectural and structural designers, with the technical implications of the geometric requirements of the formwork and the distances between the reinforcing bars, stipulate the maximum size of the coarse aggregate to be used in the concrete mixture. This parameter is relevant because it determines the amount of cement required and its corresponding environmental impact. In addition, sustainability aspects should be presented in the construction committees, which allows site managers to play a crucial role in the correct planning and selection of raw material suppliers, taking into account studies such as those proposed in this work, while the builders have the responsibility to materialize what is planned and scheduled.

In this way, under the context of the A.C.I methodology in the design of concrete mixture, the LCA could be integrated to develop a tool that allows optimizing the selection of materials. However, regulations and methodologies for the design of concrete mixtures from other continents can be coupled to implement initiatives of this type. The optimization process allowed identifying the best economic and environmental conditions for designing a mixture for a 21 MPa concrete, defining the selection of fine and coarse quarry aggregates. Although the best route is found, this limits the future implementation to one or two quarry sources, which forces other quarries to improve the production process by implementing innovative technologies that lead to defining the EDP and reducing environmental impacts from the source. Additionally, according to the A.C.I., mixtures with higher MS of the coarse aggregate require a lower cement dosage for a specific strength of concrete. This is a factor to consider in concrete production systems, as the technical literature shows that cement is the indicator that raises costs the most and generates environmental impacts. Thus, builders are called to analyze each technical, economic, and environmental component considering the project being executed.

Both embedded energy and global warming show similar responses in each of the three families of mixtures due to the demand for cement. In many cases, an inverse relationship is observed between water and the indicators of global warming and embedded energy. This pattern is associated with a high dependence on the intrinsic characteristics of aggregates, such as their morphology and degree of absorption. In addition, the results demonstrate the greater eutrophication and generation of hazardous waste from aggregates for the most optimal mixtures. This may be associated with the preparation of the aggregates, as mainly the washing of the material removes particles of size less than 75 µm like silt and clay. This process is required in aggregates as a quality control parameter, and in most cases, this particulate material is taken to tributaries in the form of sludge. This can be a focus of research to recover sludge and develop utilization processes.

Although the proposed environmental hypothesis allowed the development of an optimization tool, the fields associated with the EDPs of all materials must be validated, which evidences a broad effort on the part of private companies and the public sector with the civil, social, and natural responsibility implied by mining exploitation for construction materials.

According to Table 9, the results obtained in this research are consistent with those achieved with other tools for quantifying the environmental impact of concrete mixtures. By comparing the embedded energy results obtained in this study with the simulation results in the tool *"Green Concrete LCA web tool"* (Berkeley, n.d.), a difference of less than 0.85% was evident for all the evaluated mixtures. These results are very similar because the EDPs of cement reported by producers in Colombia are equivalent to the EDPs from the PCA (Portland Cement Association, 2014). However, in the comparison of CO_2 emissions, an approximate difference of 13% is evident. Although this difference between the results of both tools can be classified as small, it is the result of a site-specific environmental load that may depend on the aggregate extraction and production processes in the study region.

To determine system models with more holistic views, it is necessary to incorporate three aspects: i) Use of equipment and technology associated with

Type of mix (kg Portland cement / m3 of concrete mix)	Calculation tool			
	Developed by Authors - Phase 2 (Figure 3)		Green Concrete LCA web Tool *	
	GWP: Average (kg CO_2 - eq.)	NRE: Average (MJ)	GWP: Average (kg CO_2 - eq.)	NRE: Average (MJ)
266	243.90	1517.70	280.74	1512.53
290	264.80	1635.50	304.79	1629.23
316	288.00	1770.80	330.97	1755.45

* Simulation May 26, 2024, without transportation and making use of Type I Portland cement.

Table 9. Comparative quantification of environmental impact - Other tools. Source: Preparation by the authors.

the design of concrete mixtures on site, as energy consumption and technological obsolescence can be detrimental to the optimization of mixtures. ii) Use of additives to modify rheological properties of mixtures and reduce cement consumption, as well as use of active additives that improve cement performance. iii) Transportation associated with the materials from the source to the construction site could significantly modify the values obtained from the cost and impacts per evaluated mixture. This is due to the trend of an old car fleet with the prevalence of diesel, which is less efficient, generating higher CO_2 emissions. In addition, variables such as the loads transported and the relationship between density and effort per kilometer transported should be analyzed. Finally, it is necessary to implement the proposed analysis in concrete mixtures with higher strength and durability requirements. In this way, it is possible to evaluate the great potential and quantify the possible economic and environmental benefits that can be obtained by carrying out this type of analysis by programming computer tools that allow the creation of inventories and the interaction of large data flow.

CONCLUSIONS

Implementing and integrating tools that use parameterized data allows for identifying an excellent potential for innovation in the different concrete mixture dosing programs, such as the DISMECON software. The synergy between this knowledge allows establishing a new program to quantify the CO_2 emissions and other environmental impact categories.

Based on the design of mixtures and the consideration of the location data of the sources of the aggregates, together with the optimization correlations according to their characteristics, they allow projecting not only the potential impacts in each of the categories of the EDPs used, but also to make estimates as to the cost of producing the concrete. These estimates are based on the different combinations of these materials, making the process very attractive for economic efficiency in producing concrete mixtures. In addition, it promotes the appropriate decision-making about cement resistance and consumption needs.

The modeling allowed identifying optimization processes in using aggregates to manufacture concrete mixtures and to establish the effects of environmental loads when using aggregates of different sizes. Greater impacts of CO_2 emissions and embedded energy demand are found associated with the incremental consumption of cement in the mixtures, this in turn, is more demanded in the designs of mixtures that use coarse aggregate of smaller maximum size, which implies higher costs and CO_2 emissions, up to 15% higher than if they use coarse aggregates of an immediately larger maximum size.

The concrete mixtures with the lowest environmental impact are, in turn, the most economical, given that an analysis of properties (characterizations) of the aggregates is carried out and, based on these, a better proportionality of cement, which shows that sustainability and economic efficiency are compatible and have a high added value for the construction sector.

This research is expected to contribute to promoting strategies to mitigate greenhouse gases (GHG) in the construction sector. In addition, it demonstrates the need to adopt collaborative work methodologies among all actors in the construction sector, highlighting their potential and the benefits this can generate.

The research shows that it is possible to reduce environmental impacts from the fact that Life Cycle Analyses (LCA) are based on evaluations at the level of the appropriate use and optimization of materials, such as concrete, so that they are scalable and comparable, instead of relying exclusively on the implementation of innovative technologies and materials in the future; effectively contributing to the reduction of emissions and the progress towards a more sustainable built environment, more in line with the conclusions of Olsson et al.(2024) on the need to strengthen processes, to subsequently include innovative low-emission materials.

FUTURE WORKS

In future works, transport should be included to consider the site-specific environmental loads, as, in this work, different transport options were not explored nor was it determined how much their impact represents in the life cycle compared to the total impact. In addition, it will be essential to incorporate construction and demolition waste into the processes, adopting a circular engineering perspective to maximize material reuse and minimize waste. Specific eco-indicators should be developed for the construction sector that are complementary and facilitate standardization processes, allowing their comparison and implementation in other latitudes. The tool will have to be taken to the production level, integrating these future works to offer a more complete and sustainable solution in the construction industry.

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ANALYSIS OF THE IMPACT OF EDGE CERTIFICATION ON BUILDINGS: THE CASE OF PERU

UN ANÁLISIS DEL IMPACTO DE LA CERTIFICACIÓN EDGE EN EDIFICACIONES: EL CASO DE PERÚ

ANÁLISE DO IMPACTO DA CERTIFICAÇÃO EDGE EM EDIFÍCIOS: O CASO DO PERU

Mónica J. Condezo-Solano
Arquitecta
Investigadora Facultad de Arquitectura
Universidad Nacional de Ingeniería, Lima, Perú
https://orcid.org/0009-0004-2275-5057
mcondezos@uni.pe

Andrews A. Erazo-Rondinel
Ingeniero Civil
Investigador Facultad de Ingeniería
Universidad Continental, Huancayo, Perú
https://orcid.org/0000-0002-5639-573X
aerazo@continental.edu.pe (Autor de Correspondencia)

Lorena Milagros Barrozo-Bojorquez
Estudiante - Investigadora, Facultad de Ingeniería Civil
Universidad Nacional de Ingeniería, Lima, Perú
https://orcid.org/0009-0002-9700-8764
lorena.barrozo.b@uni.pe

Coraima Chantal Rivera-Nalvarte
Estudiante - Investigadora, Facultad de Ingeniería Civil
Universidad Nacional de Ingeniería, Lima, Perú
https://orcid.org/0009-0008-3629-0288
coraima.rivera.n@uni.pe

Areli Zaraida García-Puclla
Estudiante - Investigadora, Facultad de Ingeniería Civil
Universidad Nacional de Ingeniería, Lima, Perú
https://orcid.org/0009-0002-5750-3760
areli.garcia.p@uni.pe

RESUMEN

Las certificaciones ambientales, se han implementado en el sector de la construcción por los beneficios de reducción del impacto ambiental, mejora de la eficiencia energética, uso de agua, entre otros. En ese sentido, en los últimos años se ha adoptado en más de ciento cuarenta países la certificación EDGE (Excellence in Design for Greater Efficiencies). Sin embargo, pese a su popularidad; la literatura sobre los impactos en el medio ambiente, es escasa a nivel mundial y latinoamericano. Por ello, el siguiente artículo analizará el uso de EDGE en proyectos de vivienda en el Perú y mostrará las estrategias empleadas en los casos de estudio para disminuir el impacto ambiental. Para ello, se realiza una revisión literaria de EDGE y un análisis de dieciocho proyectos de edificaciones peruanos, los principales ahorros promedio obtenidos, son: 27.6% en Energía, 41.2% en Agua y 51.81% en Carbono Incorporado en Materiales. El siguiente estudio significa un aporte a los profesionales del sector construcción interesados en implementar la certificación EDGE en sus proyectos, ya que se evidencian los impactos ambientales que genera este tipo de certificación.

Palabras clave
EDGE, edificaciones verdes, eficiencia energética, sustentabilidad

ABSTRACT

Environmental certifications have been implemented in the construction sector because of the benefits of reduced environmental impact, improved energy efficiency, and water use, among others. In recent years, the EDGE (Excellence in Design for Greater Efficiencies) certification has been adopted in more than 140 countries. However, despite its popularity, the literature on its environmental impacts worldwide and in Latin America is scarce. Therefore, the following article will analyze the use of EDGE in housing projects in Peru and show the strategies employed in the case studies to reduce the environmental impact. The main average savings obtained were 27.6% in energy, 41.2% in water, and 51.81% in embodied carbon in materials. The following study aids professionals in the construction sector interested in implementing EDGE certification in their projects, as it will show the environmental impacts generated by this certification.

Keywords
EDGE, green buildings, energy efficiency, sustainability

RESUMO

As certificações ambientais foram implementadas no setor de construção pelos benefícios da redução do impacto ambiental, da melhoria da eficiência energética e do uso da água, entre outros. Nesse sentido, a certificação EDGE (Excellence in Design for Greater Efficiencies) foi adotada em mais de 140 países nos últimos anos. Entretanto, apesar de sua popularidade, a literatura sobre os impactos no meio ambiente é escassa em nível global e latino-americano. Portanto, o artigo a seguir analisará o uso do EDGE em projetos habitacionais no Peru e mostrará as estratégias empregadas nos estudos de caso para reduzir o impacto ambiental. Para isso, é realizada uma revisão da literatura sobre EDGE e uma análise de dezoito projetos de construção peruanos, sendo que as principais economias médias obtidas são: 27,6% em energia, 41,2% em água e 51,81% em carbono incorporado em materiais. O estudo a seguir é uma contribuição para os profissionais do setor de construção interessados em implementar a certificação EDGE em seus projetos, pois mostra os impactos ambientais gerados por esse tipo de certificação.

Palavras-chave:
EDGE, edifícios verdes, eficiência energética, sustentabilidade

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INTRODUCTION

The construction industry is one of the primary sources of energy consumption (Aini & Taringa, 2023) and air pollution in most countries (Li et al., 2019), and contributes to 38% of global carbon dioxide emissions (CO_2) (UNIDO, 2021). Diverse certification systems have been developed to control the impact of construction projects. The first certification system developed was BREEAM (Building Research Establishment Environmental Assessment Methodology) in the United Kingdom. It is now widely used in different parts of the world, although 80% of its certified projects are in Europe. BREEAM evaluates the sustainability of buildings throughout their life cycle, and the environmental factor is predominant in the certification (Doan et al., 2017). BREEAM has also influenced the development of other certification systems, such as LEED (Leadership in Energy and Environmental Design), which is a certification system developed by the USGBC (US Green Building Council) and is considered the most widely adopted certification system since it has been implemented in more than 160 countries and like BREEAM is mainly focused on environmental factors (Doan et al., 2017). LEED is a certification system based on scores and categories, leading to four building certification levels (Certified, Silver, Gold, and Platinum) (Marzouk, 2023). LEED also has environmental, human health, and economic benefits (Chavez-Finol et al., 2021; Elkhapery et al., 2021). Another of the certifications used is DGNB, which consists of a system developed by the GSBC (German Sustainable Building Council) in 2007 and has more than 5900 projects in more than 30 countries. This certification seeks to evaluate and certify the sustainability of buildings in Germany and internationally since it has the ability to adapt to climate, structural, legal, and cultural variations and has four types of certifications: platinum, gold, silver, and bronze (Samamé-Zegarra, 2021).

In Latin America, LEED and EDGE have been shown as the certifications with the highest acceptance. However, countries have adopted other local certifications such as CASA (Colombia), Punto Verde (Ecuador), EcoCasa (Mexico), and the Sustainable Mivivienda Program (Peru), among others (Villaseñor, 2021). According to the Colombian Council of Sustainable Construction (CCCS, 2024), in the latest LEED analysis for Latin America, 75% of projects are concentrated in the following countries: Brazil, Mexico, Colombia, and Chile, and more than 50% of projects are rated gold and platinum. LEED has presented benefits such as improved occupant health and well-being and lower building operating costs. Although LEED is a rigorous and demanding certification system, it has limited acceptance in developing countries due to its cost and complexity (Beltrán-Méndez & Nik-Bakht, 2018). The World Bank's International Finance Corporation (IFC) has responded to this need with the development of EDGE (Excellence in Design for Greater Efficiencies), an environmental certification tool for buildings available in more than 140 emerging markets (Isimbi & Park, 2022). EDGE also provides technical solutions to reduce operating expenses, reduce carbon emissions, and mitigate environmental impacts in new and existing buildings (Villaseñor, 2021).

To comply with the EDGE certification, a building must achieve a minimum of 20% savings in its three categories: energy, water, and embodied carbon in materials compared to usual local practices (Aini & Tarigan, 2023). EDGE covers different types of buildings, such as houses, apartments, hotels, stores, industries, offices, health centers, warehouses, hospitals, airports, and mixed-use (Kapoor et al., 2019; Marzouk, 2023). It can also be applied at any stage of the building life cycle, from the conceptual design to new constructions, existing buildings, and renovations.

The EDGE v3 guide (IFC, 2021) mentions that the measures being evaluated to achieve these 20% savings depend on the type of project. In the case of this research for the energy category, 34 measures proposed by the EDGE guide and software can be evaluated. Six are mandatory, and the rest are optional. This will depend on whether the energy simulation results in the EDGE software are greater than 20%. For the water category, 17 measures can be assessed, of which six are mandatory and the rest are optional. This will depend on the energy simulation results in the EDGE software. Finally, in the case of materials, 11 measures are evaluated, all mandatory.

The evaluation under the Houses and Apartments typology, on which this study focuses, is based mainly on energy and water efficiency at a residential level, emphasizing domestic systems such as lighting, heating, and appliances, as well as on water consumption in bathrooms and kitchens. Using sustainable materials and efficiency in thermal insulation is also considered to improve energy efficiency in the housing unit. On the other hand, the evaluation for the other typologies, such as industries, focuses on the efficiency of machinery and production processes, optimization of water use in industrial processes, and selection of low-embodied energy materials with efficient waste management. Meanwhile, stores focus on the energy efficiency of lighting, HVAC, and refrigeration, the reduction of water consumption in common areas, and the use of sustainable and recycled materials (IFC, 2021).

Marzouk (2023) mentions that the advantage of EDGE over LEED is the free EDGE web application that

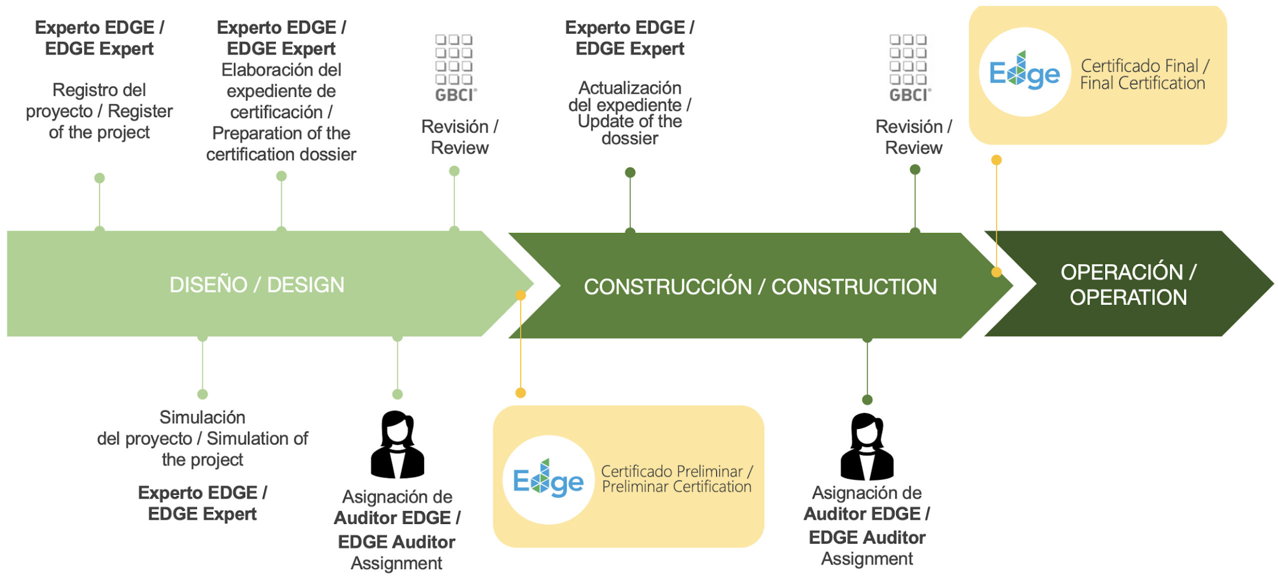

Figure 1. Timeline of the EDGE Certification. Source: Preparation by the authors.

allows a self-assessment of the building to be certified informally before the initial certification process without incurring any cost. A second advantage is its ease of understanding and achieving the certification criteria. Thirdly, EDGE has a database that allows it to adapt to the location set by the user for the project that will be designed and built. With this, collecting additional data, such as prices and weather information for the design, is unnecessary. The last advantage is the fast, interactive response that can be obtained by using the EDGE online software during the design, in addition to quickly showing the changes in water or energy or optimizing the use of construction materials. Likewise, Samamé-Zegarra (2021) mentions that the EDGE water calculation web tool makes the water analysis process simpler than other certifications such as LEED, BREEAM, or DGNB.

EDGE has been adopted in many countries. However, research on its benefits and impacts is limited, especially in Latin America, which has over 400 certified projects. Colombia has 200 certifications and the highest number of certified projects (Villaseñor, 2021), with 81% residential (Rodríguez et al., 2021). Peru is the second Latin American country for EDGE-certified projects (Villaseñor, 2021). In Peru, environmental certifications are increasingly being adopted in the market, where LEED-certified constructions lead the way, with the office building typology representing about 50% of the certified projects (Villaseñor, 2021). However, adopting LEED has certain limitations, such as using materials unavailable in the country, the reuse of construction materials, renewable energy on-site, and few certified wood suppliers (Regalado-Espinoza et al., 2021).

Another certification with rapid growth in the Peruvian market has been EDGE, which has become quite popular among real estate developers due to the municipal incentives they receive for obtaining the certification, such as the height bonus, which allows them to build more apartments (Samamé-Zegarra, 2021). The Mivivienda Sostenible Program certification promoted by the Peruvian state is used at a local level. It is optional and has been implemented since 2016. It is focused on social housing and ranges from $17,262 to $122,901. This certification evaluates six criteria: water, energy, bioclimatic, materials, waste, and urban sustainability (Samamé-Zegarra, 2021).

Given Peru's housing deficit, sustainable housing is presented as a critical solution, and EDGE is a potentially transformative tool for addressing energy efficiency and housing shortages. That is why this research aims to analyze the adoption of EDGE certification in buildings in Peru.

EDGE CERTIFICATION PROCESS

The EDGE certification process of a new building is divided into the design and construction stages and can be summarized in Figure 1.

According to the EDGE V3 guide (IFC, 2021), the process begins with the project's registration on the EDGE platform, where simulations are then carried out applying different sustainable strategies, looking to achieve the minimum required savings of 20% in the three categories contemplated by EDGE. Then, in the design stage, the certification file is made

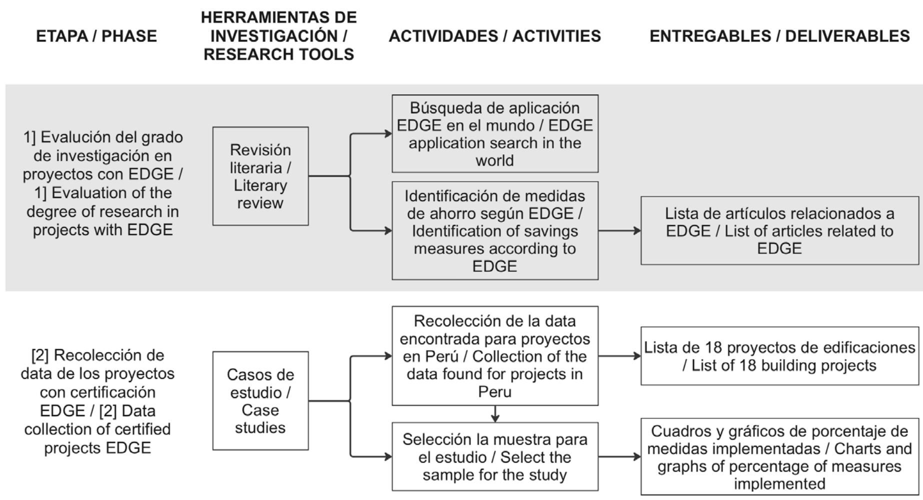

Figure 2. Methodology of the research. Source: Preparation by the authors.

and submitted for review by the EDGE Auditor and the GBCI certifying entity. After the first round of review, the observations are identified and communicated to the project team. Subsequently, the team has the opportunity to address and correct the observations before a second round of review to finally obtain the Preliminary Certification.

During the construction stage, the same process is repeated. It begins by updating the file based on the changes experienced by the project, if any. Subsequently, the EDGE Auditor is assigned, who conducts an on-site audit and, in collaboration with the GBCI, verifies compliance with all the measures adopted and implemented in the project. This process concludes with obtaining the Final EDGE Certification.

According to the EDGE V3 guide (IFC, 2021), the EDGE certification includes 3 levels based on the savings achieved:

- EDGE Certified. This is the basic level at which this recognition can be obtained: it is awarded by meeting a minimum saving of 20% in the energy, water, and embodied carbon in the building materials categories. These are the "base savings" on which the EDGE assessment is based.
- EDGE Advanced. This level rewards projects that demonstrate a minimum 40% reduction in energy, while the minimum savings in water and materials' embodied carbon are maintained at 20% as in EDGE Certified.
- Zero Carbon. This level of certification seeks the maximum reduction and compensation of the building's energy consumption. To achieve this, at least 40% of the energy must be reduced at the design stage through the implementation of strategies in the building (such as EDGE Advanced), and the missing savings to complete 100% of the energy consumption will be offset through on-site renewable sources or the purchase of carbon credits. Likewise, the minimum savings of water and embodied carbon are maintained at 20% as in the EDGE Certified level.

METHODOLOGY

Figure 2 details the research methodology. In the first stage, a literary review of EDGE was conducted using PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). In the second stage, 18 EDGE projects were analyzed.

FIRST STAGE: LITERATURE REVIEW

A literature review on EDGE was conducted using the PRISMA methodology, previously used for reviews on sustainability issues (Cao et al., 2022a; Cao et al., 2022b). The Scopus and Web of Science databases were used, with the keywords "Excellence in design for greater efficiencies." Twelve results were obtained in Scopus, 5 in Web of Science, and 50 in Google Scholar. Twenty were repeated, and 27 articles were discarded, leaving a list of 20 articles related to EDGE.

SECOND STAGE: ANALYSIS OF EDGE BUILDING PROJECTS

To select the projects to be analyzed, the EDGE web database was searched for files of project studies and new project studies (Edge Buildings, 2024). The search and exclusion criteria are detailed in Figure 3.

In the initial phase, 163 projects were identified, of which 81 lacked a specific designation and were called "housing." Another 28 projects had incomplete information, leaving 54 revised projects.

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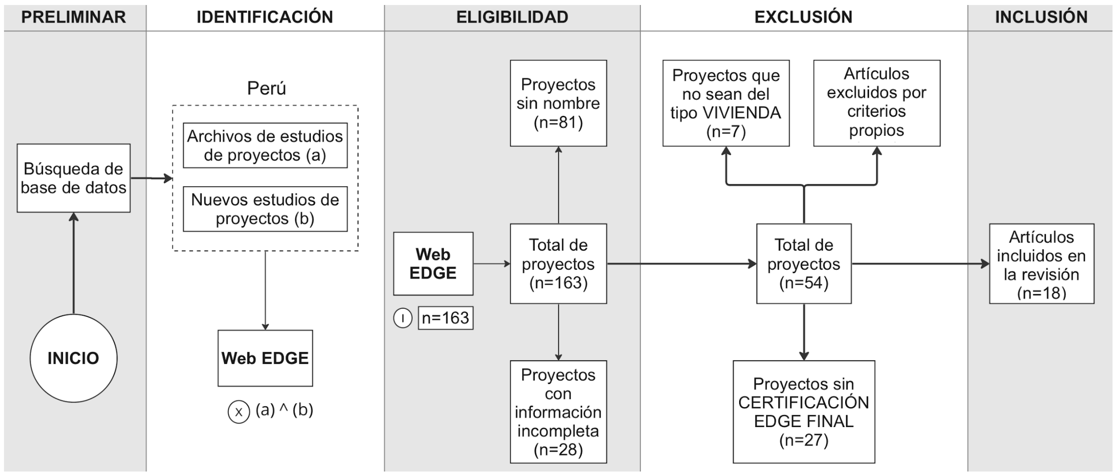

Figure 3. Selection process of projects under study. Source: Preparation by the authors.

Table 1. Eighteen residential complexes with EDGE certification. Source: Preparation by the authors.

Building code	Building's name	Surface area (m2)	Date of certification
P1	Edificio Alborada II	963.66	November 1, 2021
P2	Alcanfores 1262	4024.04	February 1, 2022
P3	Parque Verde Sur	5556.00	February 1, 2022
P4	Soleada	4825.04	November 1, 2021
P5	Parque Club	4509.69	September 1, 2021
P6	Madrid Amistoso	3208.62	September 1, 2021
P7	Madrid en Vivo	5274.93	October 1, 2020
P8	Conde de la vega	2834.00	December 1, 2020
P9	Hermano Lobo 188	2770.00	September 1, 2019
P10	Golf Los Incas	5188.00	November 1, 2017
P11	Edificio Manco Cápac 860	3675.75	May 19, 2023
P12	Multifamiliar Farah	3140.75	April 21, 2023
P13	Lumiere 7 - Llosa Edificaciones	5814.82	March 8, 2023
P14	Casimiro Ulloa 227	3608.12	August 22, 2023
P15	Edificio Multifamiliar Laureles	8367.14	January 29, 2024
P16	Edificio Multifamiliar Today	6725.39	January 17, 2023
P17	Edificio Multifamiliar Túnez 448	1643.72	June 13, 2023
P18	Edificio Helsinki	1848.3	January 29, 2024

In the next phase, nine projects were excluded, seven structures were not of the building type, and two were eliminated due to inconsistent information. Twenty-seven projects without final EDGE certification were also discarded, as the savings data are more reliable in the final certification. As a result, 18 residential buildings with Final EDGE Certification were obtained, as detailed in Table 1.

RESULTS

LITERATURE REVIEW

After the literature review, 20 articles were identified, as detailed in Table 2.

Table 2 shows 20 articles developed in the five continents, mostly in developing countries. Of the 20

Table 2. Articles related to EDGE. Source: Preparation by the Authors.

No.	Author	Country	EDGE Measurement	EDGE concept implemented
1	Azouz & Elariane (2023)	Egypt	Energy Efficiency	EDGE calculator to calculate energy efficiency.
2	Ayanrinde & Mahachi (2023)	Nigeria	Energy efficiency, water, and materials	CO2 footprint measurement.
3	Velázquez Robles et al. (2022)	Mexico, Puerto Rico, and Indonesia	Energy Efficiency	Use of EDGE software to calculate energy savings.
4	Bochare & Bagora (2022)	India	Energy efficiency, water, and materials	EDGE to evaluate energy, water, and material efficiency in sustainable construction.
5	Kapoor et al. (2019)	Does not specify	EDGE for urban developments	Proposal of an EDGE GUD tool for Urban Green Developments.
6	Kartikasari et al. (2018)	Indonesia	Energy Efficiency	Use of EDGE software to simulate energy efficiency measures.
7	Saberi & Kapoor, (2016)	United Kingdom	Energy Efficiency	Evaluation of the new EDGE measurement and its impact on energy savings.
8	Isimbi & Park (2022)	South Africa	Energy efficiency, water, and materials	EDGE software to calculate energy savings, water, embodied energy in materials and annual CO2 emissions.
9	Marzouk (2023)	Oman	Energy efficiency, water, and materials	EDGE software to calculate the energy, water, and material savings of a base case vs. a modified design case.
10	Dlamini & Yessoufou (2022)	South Africa	User evaluation on energy and water	Evaluates the barriers, opportunities, and users' perceptions about using energy and water in a residential complex.
11	Ibrahim et al.(2023)	Egypt	Energy efficiency, water, and materials	Analysis of the EDGE application to calculate the energy, water, and materials' embodied carbon savings.
12	Beltran-Mendez & Nik-Bakht (2018)	Colombia	Feasibility of implementation in the Colombian market	Evaluation of the characteristics of EDGE compared to other certifications regarding cost, operability, and penetrability.
13	Indriyati & Izzah (2022)	Indonesia	Water	To measure the efficiency of water use in a university building.
14	Tarigan & Kartikasari (2016)	Indonesia	Energy Efficiency	The EDGE calculator was used, and an energy saving of 28% was generated
15	Aini & Tarigan (2023)	Indonesia	Energy efficiency, water, and materials	EDGE software to calculate the energy, water, and material savings of a base case vs. a modified design case.
16	Rodríguez et al.(2021)	Colombia	Analysis of EDGE Projects (Energy Efficiency and Water)	Lists the EDGE and LEED energy and water savings in Colombia
17	Setyowati et al. (2020)	Indonesia	Water efficiency	Use of EDGE software and manual measurement to calculate water efficiency in a water treatment scenario
18	Atolagbe et al. (2023)	Nigeria	Energy efficiency, water, and materials	EDGE software for estimating energy consumption reduction in a university building
19	Agyekum et al., (2023)	Ghana	User evaluation of indoor air quality	Indoor environmental quality assessment (IEQ) in EDGE buildings,
20	Samamé-Zegarra (2021)	Peru	Water efficiency	Comparison of water efficiency between EDGE, LEED, BREEAM, HQE, DGNB, and Mivivienda Sostenible Program

studies, four are focused on Latin America, two on Colombia (Beltrán-Méndez & Nik-Bakht, 2018; Rodríguez et al., 2021), one in Peru (Samamé-Zegarra, 2021), and one in Mexico and Puerto Rico (Velázquez Robles et al., 2022), which represents a low amount compared to the certified projects in Latin America.

Regarding the energy category, nine articles in Table 2 address this topic (1, 3, 6, 8, 9, 14, 15, 17, and 18). These focus on using the energy analysis software provided by the EDGE online tool, which allows designing a project efficiently and freely, authorizing the choice of different ecological measures that generate more significant energy savings. A stand-out advantage of EDGE is its free online self-assessment tool, which facilitates pre-assessing a building's design before starting the official certification process (Marzouk, 2023). The EDGE software simulated energy efficiency measures in Indonesia, identifying nine measures that could achieve 18.9% savings (Kartikasari et al., 2018). In Egypt, the EDGE software was applied to calculate energy savings (Azouz & Elariane, 2023). In Mexico, Puerto Rico, Indonesia, and the United Kingdom, the EDGE software was also used to calculate energy savings (Velázquez Robles et al., 2022).

Regarding water use efficiency (13,17, 20), Table 2 has three articles that explore and analyze water efficiency with the help of EDGE software for simulations of proposed scenarios. The application was mainly used due to its ease, speed, and affordability (Samamé-Zegarra, 2021; Setyowati et al., 2020). In the case of articles 12 and 16, a comparison is made between the EDGE certification and others, which allows assessing the feasibility of its application in projects according to costs or operability. According to Beltrán-Méndez and Nik-Bakht (2018), EDGE has a lower cost and greater operability than other certifications, such as LEED, which may be behind its insertion in the Colombian market.

In articles 10 and 19, user perspectives are evaluated, where a lack of knowledge about the concepts of environment and sustainability was evidenced, in addition to the low awareness of the benefit of implementing energy and saving measures in buildings, suggesting a greater diffusion of these. On the other hand, there is only one article related to indoor air quality (EIQ) in EDGE buildings. Although this is not a concept analyzed by EDGE, Agyekum et al. (2023) evaluate the comfort parameters that should be considered based on an EDGE certification.

At a Latin American level, the implementation of EDGE certification in Colombia and Peru has common points. In Colombia, Rodríguez et al. (2021) mention that a concerted effort by companies and the government to promote sustainable construction has been observed, in line with Resolution 0549 of 2015. The EDGE certification stands out for its ease of use and low cost, facilitating its adoption in the country. Government strategies and collaboration with the private sector have been vital for EDGE to aspire to capture 20% of the construction market in the coming years. In the case of Peru, Samamé-Zegarra (2021) mentions that real estate developers have adopted EDGE due to local incentives, such as increasing the building's height on having the certification. In both countries, residential projects have the highest number of certified projects; in the case of Colombia, it is close to 80% (Rodríguez et al., 2021) and 50% in the case of Peru (Samamé-Zegarra, 2021). Another common point is that the authors of both countries have mentioned the importance of the EDGE online tool, highlighting its importance and ease of use for water and energy (Beltrán-Méndez & Nik-Bakht, 2018; Rodríguez et al., 2021; Samamé-Zegarra, 2021).

SUSTAINABILITY ANALYSIS OF THE PROJECTS UNDER STUDY

The technical solutions in energy, water, and materials embodied carbon of the 18 projects are detailed in the corresponding tables. It is highlighted that the Farah and Today buildings lead in implementing strategies in all categories of the EDGE standard, while the Golf Los Incas building has fewer implemented strategies. Buildings certified under the EDGE standard are crucial in mitigating environmental impact, significantly contributing to the fight against climate change. None of the 18 buildings achieved the EDGE Advanced Certification in the Zero Carbon Certification.

ENERGY AND ENERGY-SAVING MEASURES

Table 3 shows the application percentage of the EDGE v3 Energy measures in the studied buildings, classified into energy saving (78.4%), energy generation (13.5%), and energy measurement (8.1%). The design of the buildings focused on efficiency and reduction of consumption and also included strategies implemented during the design and construction stage, such as lighting controls, reflective paint on ceilings and walls, LED lighting, reduction of the window-wall ratio, low thermal transmittance glazing, exterior shading devices, roof insulation, and the adoption of photovoltaic solar energy. Seeking to avoid thermal bridges, energy efficiency was optimized by reducing the window-wall ratio, low thermal transmittance glazing, and insulation on ceilings and walls, which generated clear savings in the electricity bills of the end owners.

Table 3. Summary of technical solutions related to the Energy category. Source: Preparation by the authors.

Technical solutions	Percentage of buildings with solutions
E01*: Lower proportion of glass on the exterior facade	100.00%
E02: External solar control devices	44.44%
E03: Reflective paint/roof tiles	22.22%
E04: Reflective paint for external walls	5.56%
E05*: Ceiling insulation	50.00%
E06*: Thermal insulation of external walls	44.44%
E07: Glass with a low-emissivity coating	33.33%
E12*: Air conditioning system	5.56%
E33: Energy-saving light bulbs	66.67%
E34: Lighting controls	33.33%
E42: Photovoltaic solar energy	16.67%

* Mandatory measure

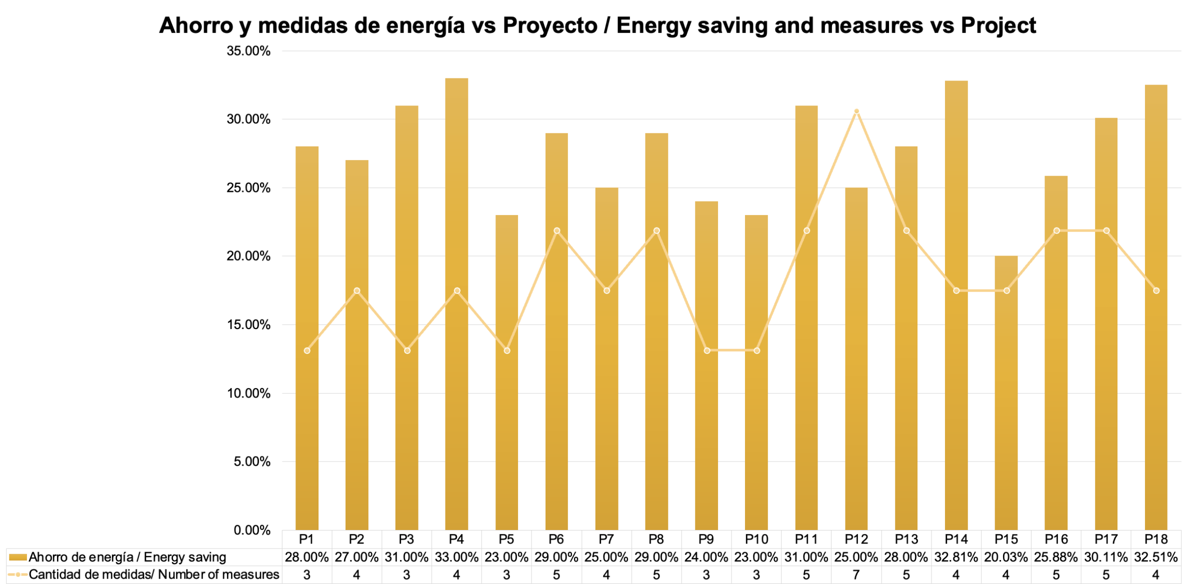

Figure 4. Energy savings against project measures. Source: Preparation by the authors.

According to local regulations, the evaluated projects achieved an average energy savings of 27.6% compared to the base case; between 2017 and 2024, energy savings fluctuated between 20% and 33%. Soleada led with 33%, followed by Casimiro Ulloa with 32.81%. Laureles had the lowest energy savings, with 20.03%, followed by Parque Club and Golf Los Incas, with 23%.

Most buildings reduced the glazed area proportion on the facade, minimizing thermal gains and maintaining interior comfort. However, Madrid en Vivo opted for efficient HVAC equipment in the housing units, which did not significantly affect energy savings. In addition, Camfores, Manco Cápac, and Lumiere implemented photovoltaic panels to cover the energy demand in common areas. Figure 4 shows the number of measures adopted by each project under study. However, it shows that the energy savings achieved are not necessarily related to the number of measures implemented. This is because each project has unique characteristics, such as the architecture of the project, the glazing proportion on the facade, and elements on which the evaluation of the measures will depend.

WATER AND WATER-SAVING MEASURES

Of the three EDGE categories, the Water category had the fewest strategies. The water-related strategies focus on controlling the consumption of bathroom

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Table 4. Summary of technical solutions related to the Water category. Source: Preparation by the authors.

Technical solutions	Percentage of buildings with solutions
W01*: Water-saving shower heads	94.44%
W02*: Efficient water-saving faucets for all bathrooms	100.00%
W04*: Efficient water-saving toilets for all bathrooms	83.33%
W08*: Water-saving kitchen faucets	100.00%
W15: Wastewater treatment and recycling system	5.56%

* Mandatory measure

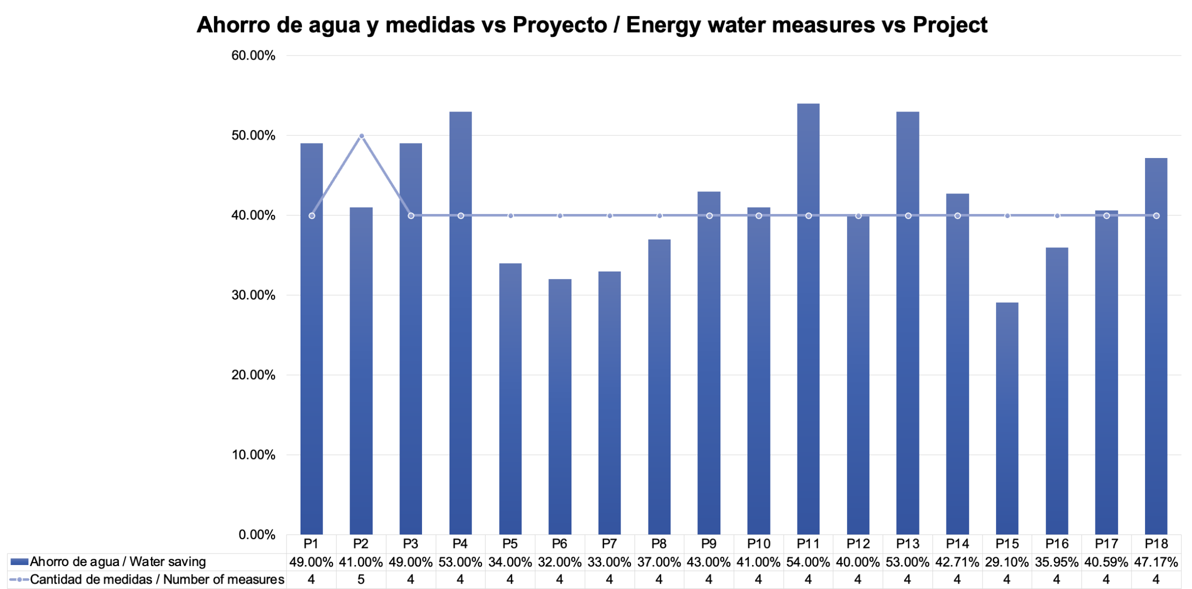

Figure 5. Water saving against project measures. Source: Preparation by the authors.

and kitchen faucets and sanitary equipment. Low-flow faucets were installed to reduce water and energy consumption intrinsically related to hot water consumption. Almost 100% of the buildings have implemented strategies such as installing low-flow faucets in bathrooms and kitchens, low-flow shower heads, and efficient single—or double-flush toilets.

On the other hand, 6% of the buildings implemented gray water treatment plants to reuse the water recovered on-site for toilets and irrigating vegetated areas, contributing to the end water savings (Table 4).

Reducing water consumption is extremely important due to the water stress that Lima is currently experiencing. The average water saving was 41.92%. The Manco Cápac Building came first, with the highest savings at 54%, followed by Soleada and Lumiere with 53%. Soleada stands out regarding energy and water savings among all the evaluated buildings. The lowest savings achieved were obtained by Friendly Madrid with 32%, followed by Live Madrid with 33%. Even though Camfores was the only building that implemented a gray water treatment system on-site as an alternative source of drinking water, its savings remained close to the average of 41%. Figure 5 shows the savings achieved versus the measures taken. It was perceived that the percentage of water savings achieved is not necessarily related to the number of measures implemented. This is due to the specifications of the sanitary equipment and faucets. In addition, there are four mandatory compliance measures in this category, and there is only one additional project, which measures W15 (Wastewater Treatment and Recycling System).

MITIGATION STRATEGIES FOR MATERIALS' EMBODIED CARBON

The analyzed projects have considered versions 2 and 3 of EDGE. For version 2, 6 mandatory measures are indicated, and in the case of version 3, there are 11 mandatory measures. In the construction of buildings, diverse materials are used in structural and architectural elements, such as floor slabs, ceiling slabs, interior and exterior walls, floor finishes, window

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Table 5. Summary of technical solutions related to the category of Materials' Embodied Carbon. Source: Preparation by the authors.

Construction materials	Percentage of buildings with solutions
M01*: Floor slabs	
Concrete slab reinforced in situ	44.44%
Lightweight concrete slab	44.44%
Lightweight concrete slab with polystyrene blocks	27.78%
M02*: Ceiling slabs	
Concrete slab reinforced in situ	44.44%
Lightweight concrete slab	61.11%
Lightweight concrete slab made of polystyrene blocks	27.78%
M03*: Interior walls	
Medium-weight hollow concrete blocks	44.44%
Wall reinforced in situ	66.67%
Aerated concrete blocks in autoclave	22.22%
Hollow bricks (with holes) with internal and external plaster	16.67%
Face bricks and concrete blocks	11.11%
M04*: Exterior walls	
Medium-weight hollow concrete blocks	38.89%
Wall reinforced in construction	11.11%
Aerated concrete blocks in autoclave	22.22%
Hollow bricks (with holes) with plaster on both sides	22.22%
M05*: Floor finishes	
Ceramic tile	66.67%
Vinyl floor	11.11%
Laminated wooden floor	55.56%
Terracotta tiles	11.11%
M06*: Window frames	
Aluminum	72.22%
M09*: Insulation of ceiling slabs	
Polystyrene	11.11%
Cellulose	16.67%

*Medida obligatoria

frames and glazing, screens, and insulation in the envelope. The concrete slab reinforced in situ and the lightened concrete slab were used in 44% of the buildings for the floor slabs. The lightened concrete slab prevailed in 61% of the ceiling slabs, followed by the reinforced concrete slab in situ in 44%. The exterior walls were built mainly with walls reinforced in situ (67%) and concrete blocks with medium-weight gaps (44%). In interior walls, concrete blocks with dense medium-weight gaps were the most used (39%), followed by autoclaved aerated concrete blocks (22%). In floor finishes, ceramic tiles and laminated wood flooring were applied in 67% and 56% of the buildings, respectively. Aluminum window frames were predominant in 72% of the cases. The insulation in the roof slabs and the slabs with direct contact with the ground were made with polystyrene bricks in 11% of the evaluated buildings (Table 5).

The analysis of the construction materials conducted under the corresponding category is more exhaustive and detailed since an analysis of the life cycle of each material is made. Therefore, the lower the carbon equivalent generated throughout the life cycle of the material to be used, the lower the carbon footprint emitted and, in turn, the lower the impact on the planet. The average embodied carbon savings is 51.81%. In general, the Madrid en Vivo and Golf Los Incas buildings achieved the highest savings, with 69% demonstrating that they mitigated their carbon footprint during construction. Multifamiliar Farah obtained the lowest savings, with 30%, followed by Conde de la Vega with 35%. The carbon equivalent is established based on the material chosen and used in the buildings' construction stage. This can be reduced with the correct choice of material. For this, the EDGE software will be a great ally in the choice process since it will allow making the respective simulations based on the predetermined embodied carbon for each existing material and thereby project the savings in each respective certification category.

Figure 6 shows the savings achieved versus the measures taken. However, the percentage of embodied carbon savings achieved is not necessarily related to the number

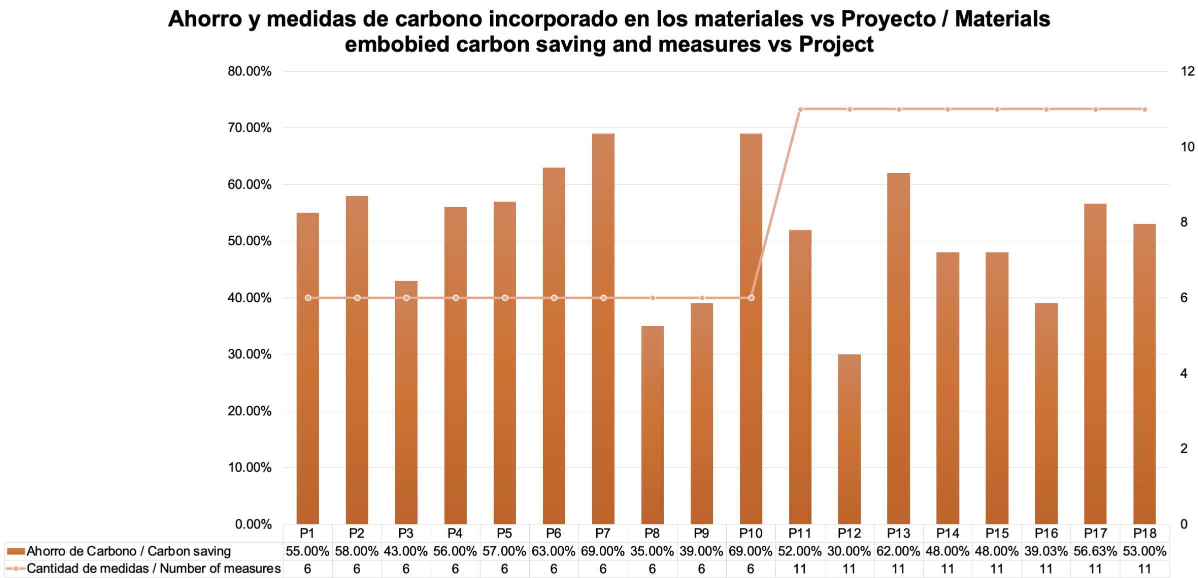

Figure 6. Embodied carbon savings against the project's material measures. Source: Preparation by the authors.

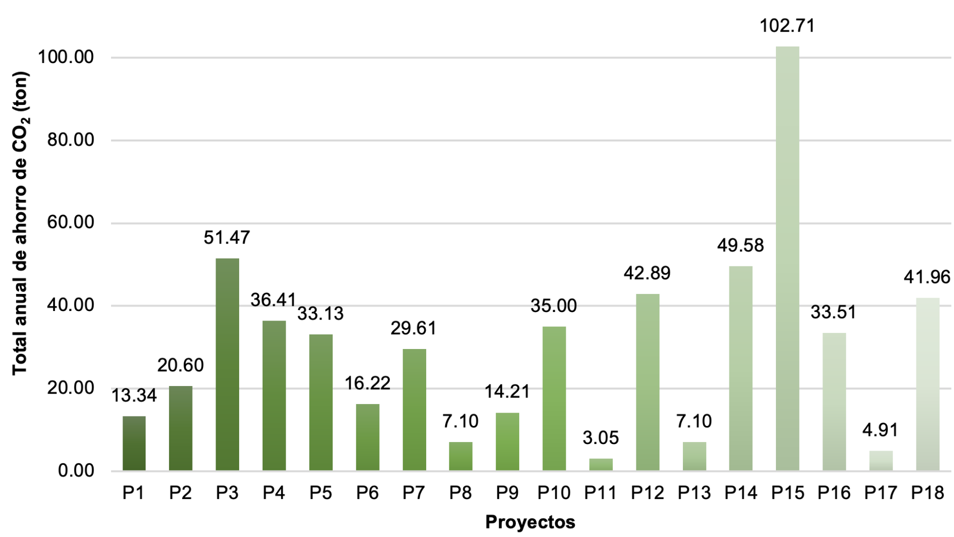

Figure 7. Total annual CO2 savings by Project. Source: Preparation by the authors.

of measures implemented. This is due to the choice of sustainable materials for building construction.

TOTAL ANNUAL CO_2 SAVINGS

The average CO_2 mitigation value for the buildings under study is 30.12 tons of CO_2 equivalent a year. It is essential to note that the CO_2 mitigation varies significantly, ranging from 3.05 to 102.71 tons. This contrast in the CO_2 savings between buildings is attributed to the diversity in the range of the evaluated structures. In particular, it is noted that Laureles achieved the highest annual CO_2 savings, reaching 102.71 tons, followed by Parque Verde Sur with 51.47 tons. On the other hand, the Manco Cápac Building registered the lowest savings, with only 3.05 tons of CO_2. Figure 7 graphically illustrates the total annual CO_2 savings for each evaluated building.

DISCUSSION

Based on the analysis, most of the projects studied are focused on the city of Lima. Due to geographical and regulatory characteristics, the results could vary if more data is obtained from other sectors of Peru.

In Peru, the implementation of EDGE has positively impacted the energy aspect of buildings. The measures adopted include the reduction of the glazing proportion on the exterior facade, external solar control devices, roof insulation, thermal insulation of external walls, glass with low-emissivity coating, energy-saving light bulbs, and lighting controls. The average energy savings achieved was 27.6%, slightly lower than the 29.7% recorded in a similar study in South Africa (Isimbi & Park, 2022), attributable to climatic conditions and local regulations.

Kartikasari et al. (2018) also highlight the improvement of energy efficiency using EDGE in Indonesia.

In the case of Latin America, in Colombia, new projects certified as sustainable buildings, more than 50% meet the minimum energy and consumption reduction percentages. In the case of the EDGE methodology, 24% did not meet the energy reduction percentage, 12% the water consumption, and 6% both. This does not imply a contradiction in what determines sustainable construction since obtaining certifications such as EDGE or LEED includes other quantifiable items that allow achieving certification (Rodríguez et al., 2021). On the other hand, with the implementation of EDGE, in the case of Mexico, significant reductions were obtained in energy demands (38.52%) and water consumption (46%) (Velázquez Robles et al., 2022). In the case of Peru, EDGE can be an important tool for water saving because a large part of the population of Peru is located on the coast, where water ends up being a vital resource (Samamé-Zegarra, 2021).

Under the water category, the measures adopted in Peru included water-saving shower heads, efficient faucets, efficient toilets, and a wastewater treatment and recycling system, which achieved an average savings of 41.92%. This result exceeds the savings of 31% recorded in a comparative study. The Peruvian buildings also opted for an alternative source of drinking water through the wastewater treatment and recycling system. Likewise, research in Mexico shows a 46% saving in water consumption, where measures such as low-flow showers and faucets, the rainwater collection system, and recycled gray water were used (Velázquez Robles et al., 2022).

As for embodied carbon, the most used materials in Peru were concrete slabs reinforced in situ, medium-weight hollow concrete blocks, and ceramic tiles. The average embodied carbon savings was 51.81%, slightly lower than the 54% observed in South Africa, where the reuse of structural elements was considered.

In addition to the results obtained, the projects certified under the EDGE standard have demonstrated clear environmental benefits, especially in reducing CO_2 equivalent emissions throughout the entire life cycle of buildings. These positive impacts are due to the implementation of energy efficiency, efficient water use, and sustainable material selection strategies, consolidating EDGE as an essential tool for promoting sustainable construction and climate change mitigation strategies.

CONCLUSIONS

This study shows the impact of EDGE certification on buildings in Peru. 557 units of 18 certified residential buildings were analyzed from November 1st, 2017, to January 29th, 2024, obtaining average savings of 27.6% for energy, 41.2% for water, and 51.81% for materials' embodied carbon.

The buildings reduced energy consumption by optimizing the window-wall ratio, the envelope's thermal insulation, low thermal transmittance glazing, and gas-powered water heaters. In addition, water efficiency measures were implemented, such as low-consumption faucets, sanitary equipment, and an alternative drinking water source through a gray water treatment plant for reuse in toilet flushing and irrigation of green areas. As for the construction, the frequent use of concrete slabs reinforced in situ and lightened concrete slabs on floors stands out, while those reinforced in situ and concrete blocks with medium-weight gaps were preferred on exterior walls. Concrete blocks with dense medium-weight gaps were predominant in interior walls. Ceramic tiles and laminated wood flooring were the most common floor finishes, and aluminum was preferred for window frames. In insulation practices, polystyrene bricks were frequently used in roof slabs and slabs with direct contact with the ground.

The research has limitations regarding the number of studies because only 18 final certificates were analyzed, and the results could vary with a more significant number of projects. The authors suggest replicating the following study in other countries to see the impact of the EDGE certification and conducting analyses to explore whether there is a correlation between the m^2 and the savings obtained. Also, it is suggested that the factors that generate the adoption of the EDGE certification or other environmental certifications be investigated.

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THE VOLUNTARY NATURE OF AN ENERGY RATING AS A CAUSE OF CONSUMER MISINFORMATION AND GREENWASHING PRACTICES

LA VOLUNTARIEDAD DE UNA CALIFICACIÓN ENERGÉTICA COMO CAUSA DE DESINFORMACIÓN EN LOS CONSUMIDORES Y PRÁCTICAS DE GREENWASHING

A VOLUNTARIEDADE DE UMA CLASSIFICAÇÃO ENERGÉTICA COMO CAUSA DE DESINFORMAÇÃO PARA OS CONSUMIDORES E DE PRÁTICAS DE GREENWASHING

Macarena Díaz de Valdés-Haase
Doctora en Derecho
Docente- investigadora, Facultad de Derecho
Universidad Andres Bello, Santiago, Chile
https://orcid.org/0000-0001-6385-5901
macarena.diazdevaldes@gmail.com

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RESUMEN

El objeto de esta investigación es la calificación de eficiencia energética de las viviendas comercializadas por inmobiliarias y constructoras en la comuna de Santiago, Chile. De este modo, se analizó, a la luz de la normativa vigente, la publicidad contenida en las páginas web de 45 proyectos inmobiliarios en venta durante el mes de junio del 2024. En cuanto a la metodología utilizada para llevar a efecto este estudio, se recurrió, por un lado, al método dogmático –propio de los estudios realizados en el ámbito jurídico– y, por otro, a los métodos empírico-analítico y comparativo. Los resultados permiten concluir que la voluntariedad del etiquetado energético y la regulación existente en este ámbito deja expuesto al consumidor inmobiliario a decisiones de compra desinformadas e incluso, a prácticas de greenwashing ya que, no le es posible comprobar la veracidad de las afirmaciones publicitarias realizadas. Todos los proyectos analizados tienen un valor que va desde las 2000 a las 4000 UF y apuntan, en consecuencia, a los consumidores pertenecientes a la clase media (sector C2 y C3).

Palabras clave
consumidor inmobiliario, greenwashing, ecoblanqueo o lavado verde de imagen, eficiencia energética, información veraz

ABSTRACT

This research aims to review the energy efficiency rating of homes sold by real estate companies and construction firms in the city of Santiago. Thus, the advertising on the websites of 45 real estate projects for sale in June 2024 was analyzed in light of the current regulations. Regarding the methodology used to carry out this study, both the dogmatic method —typical of studies conducted in the legal field— and the empirical-analytical and comparative methods were employed. The results conclude that the voluntary nature of energy labeling and the existing regulations expose real estate consumers to uninformed purchasing decisions and even to greenwashing practices, as they cannot verify the truthfulness of advertising claims. All the analyzed projects are priced between 2,000 and 4,000 UF (US$79,100 to $158,200 – July 2024), consequently targeting consumers belonging to the middle class (C2 and C3 sectors).

Keywords
real estate consumer, greenwashing, eco-whitening or greenwashing, energy efficiency, truthful and timely information, energy rating of homes.

RESUMO

O objeto desta pesquisa é a classificação de eficiência energética de residências comercializadas por empresas imobiliárias e de construção na municipalidade de Santiago, Chile. Para tanto, a publicidade contida nos sites de 45 projetos imobiliários à venda durante o mês de junho de 2024 foi analisada à luz das normas vigentes. Quanto à metodologia utilizada para realizar este estudo, recorremos, por um lado, ao método dogmático - típico de estudos realizados no âmbito jurídico - e, por outro, aos métodos empírico-analítico e comparativo. Os resultados levam à conclusão de que a natureza voluntária da etiquetagem energética e as regulamentações existentes nesse campo deixam o consumidor de imóveis exposto a decisões de compra desinformadas e até mesmo a práticas de greenwashing, já que não é possível verificar a veracidade das alegações publicitárias feitas. Todos os projetos analisados têm um valor que varia de 2.000 a 4.000 UF (de 436 a 872 mil reais – julho 2024) e, consequentemente, são voltados para consumidores de classe média (setor C2 e C3).

Palavras-chave:
consumidor imobiliário, greenwashing, eco-lavagem ou greenwashing, eficiência energética, informações verdadeiras e oportunas, classificação energética de residências.

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INTRODUCTION

Not only is the construction phase of a building a source of pollution but so is its operation, given the emissions produced from its use and the consumption of energy and water in its operation (Alavedra et al., 1997). In fact, buildings are one of the primary sources of energy demand and carbon dioxide (CO_2) emissions into the atmosphere (Wegertseder et al., 2014; Chavarry et al., 2023). In this vein, the factor that influences buildings' environmental impact most during their useful life is energy consumption for heating and cooling (Castillo, 2019).

Efficient building design can play a fundamental role in the fight against climate change, and incorporating strategies to reduce environmental impact and increase eco-efficiency in the entire value chain can help reduce Greenhouse Gas (GHG) emissions. In this sense, it is essential to recognize that energy consumption is a crucial sustainability indicator, and decreasing its use is a significant step towards sustainable construction principles (Muñoz et al., 2012). By providing environmental benefits, energy efficiency also brings economic savings for the building's users (Chavarry et al., 2023).

According to a study conducted in February 2021[1], Chilean consumers are increasingly interested in purchasing sustainable or efficient housing. In fact, the study showed that 80% of those who intend to buy a home in the Metropolitan Region would value that it is sustainable. However, in most cases, the basis for the decision does not rest, as one might think, on caring for the environment but on the expected savings.

However, it is observed that most residential projects are advertised without mentioning energy efficiency among their real estate benefits or attributes. Although some projects have an energy rating, they only display the respective seal. Most do not explain the attributes or amenities that make the homes or the project gain such a rating and the implications that derive from it. On the other hand, this scenario facilitates misleading advertising, particularly greenwashing, which consists of marketing a product as sustainable or environmentally friendly when it is not (Lyon & Maxwell, 2011).

In this way, real estate and construction companies advertise different attributes, claiming energy savings. The lack of information, in this regard, makes this type of message decisive in the purchase decision. However, having specific attributes – for example, thermopanels or special ventilation systems - does not necessarily make the house efficient or produce energy savings. Moreover, it has been argued that there is a proliferation of misleading environmental claims in advertising real estate projects (Tateishi, 2018; Shahrim et al., 2017; Cheng et al., 2023).

In this context, this research aims to elucidate how voluntary energy labeling influences the advertising content of real estate projects and determine which position consumers take when faced with advertising claims related to energy savings and efficiency.

METHODOLOGY

The dogmatic method – typical of studies carried out in the legal field – was used to analyze current thermal insulation and energy efficiency regulations. Expressly, Law N°21.305 of 2021 on Energy Efficiency (EEL) and the Thermal Regulation (TR) contained in Article 4.1.10 of SD No. 47 of 1992 [MINVU]. This method was also used to determine whether advertising claims related to energy efficiency are integrated into the sales contract in light of Law No. 19,496 of 1997 on the Protection of Consumer Rights (PCRL). At the same time, misleading advertising and greenwashing were studied from a legal perspective.

On the other hand, the empirical-analytical method was used to determine the importance that real estate and construction companies attach to energy efficiency when advertising their real estate projects and, in particular, if real estate consumers can make an informed purchase decision when choosing their home. In this way, the advertising of 45 real estate projects offered for sale in the municipality of Santiago during

1 The study was carried out by StatKnows on behalf of and with technical support from EBP Chile. The survey was applied to a probabilistic sample of 3,765 people over the age of 20 who were looking for a home during the last three months in the Metropolitan Region. The estimated sampling error is 1.21%, with a confidence level of 95%. Information is available at: https://www.elmostrador.cl/generacion-m/2021/02/22/encuesta-revela-amplias-oportunidades-del-nuevo-mercado-del-desarrollo-inmobiliario-para-el-ahorro-con-positivo-impacto-ambiental/

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June 2024, disseminated through the websites of the respective real estate agencies or construction companies, was examined.

The comparative method was then used to obtain statistically representative data. Using these, the percentage of projects whose advertising lacks the necessary information to make good purchasing decisions and those whose advertising can rightly be qualified as misleading or at least confusing was identified.

RESULTS AND DISCUSSION

SUSTAINABILITY, ENERGY EFFICIENCY, AND THERMAL INSULATION

So-called "sustainable construction" seeks to optimize resources in building planning, design, construction, and operation processes to minimize environmental and health impacts (Framework Collaboration Agreement on Sustainable Construction, 2012). One of its key elements is the reduced use of energy sources. In this sense, it should be noted that the amount of energy used to heat a building depends mainly on its thermal insulation. In fact, homes consume almost 15% of the country's total energy, mostly used for heating (División de Energías sostenibles, Public Sector Results Report - Law 21.305, 2022). This shows the close relationship between the Thermal Regulation (TR) and the Energy Efficiency Law (EEL).

The TR establishes the minimum thermal transmittance conditions that must be met by the elements in the housing envelope (Article 4.1.10 N°1.A). The envelope is "the mechanism of a building to ensure indoor habitability and comfort, and energetically, it is a decisive factor of energy efficiency" (Escorcia et al., 2012, p. 565). The Official Chilean Standard NCh 853-2007 (repealed in 2008) defined thermal transmittance as the "heat flux that passes through the element's unit surface area and per degree of temperature difference between two environments separated by said element." Thus, the lower the thermal transmittance, the better the house's insulation and the lower the energy expense.

The elements of the housing envelope included in the current Chilean TR are the roofs (incorporated in 2000), the perimeter walls, and the ventilated lower floors (both included in 2007). However, these minimum conditions need to be improved, as they do not effectively contribute to energy efficiency and environmental care (Holm Oaks et al., 2019; Escorcia et al., 2012). Its most significant deficiencies are related to thermal zoning and the approach to the requirements imposed on construction (Caldera, 2012).

In the middle of 2013, updating the TR began. The original proposal covered essential aspects to limit energy demand and improve the building's indoor environmental quality (thermal insulation of ground floors, doors, and windows; airtightness and ventilation). However, in 2021, when the resulting standard (NTM 011) was about to be decreed, around 900 architects expressed their concerns, arguing that it was a limitation on the freedom of architectural design. The Association of Architects' Offices (AOA) formed a working group to develop an alternative proposal, which was supported by the Chilean Chamber of Construction (CChC) and presented to the Ministry of Housing and Urbanism (Trebilcock, 2023). As a result, stagnation in the update has affected consumers and compliance with the government's goals in environmental matters, which were included in 2022's National Energy Efficiency Plan [2022-2026].

Finally, on May 16th, 2024, the Office of the Comptroller General of the Republic registered the decree amending the OGUC (General Ordinance on Urban Planning and Construction)– specifically its Articles 4.1.10 and 4.1.10 bis – which updates the standards and technical standards related to thermal conditioning. Consequently, among other things, it incorporates improvements associated with the thermal requirements of walls, ventilated floors, and stem walls. However, according to the first of its transitional provisions, these modifications will apply to new homes 18 months after publication in the Official Gazette. Therefore, seeing the effects of the update will take even longer.

The EEL, for its part, in its article 3, paragraph 2, provides that public buildings, commercial buildings, office buildings, and homes must have an energy rating (CEV, in Spanish) similar to that of cars or appliances to obtain their definitive reception. According to the Ministry of Housing and Urbanism's "Manual for the Energy Rating Procedures of Homes in Chile" (CEV Manual, 2019), a home's energy rating "consists of determining its energy efficiency, using an energy rating report and an energy efficiency label." Consequently, it reflects how the building behaves from an energy perspective. More specifically, it is "a theoretical estimation of the energy demand for heating, cooling, domestic hot water, and lighting." It is presented comparatively to a model dwelling and has an eight-level rating scale, ranging from

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"A+" to "G," the latter being the least efficient (CEV Manual, 2019). On the other hand, real estate projects in the construction process must have a temporary "preliminary energy rating." Hence, the preliminary rating is made on projects with the respective building permit approved by the Director of Municipal Works, and the Rating is on projects that already have the final reception (Article 3, paragraph 2 of the EEL).

Thus, the EEL modified the scenario regarding sustainability; however, it still cannot be applied to housing. In fact, it started to govern housing in February 2023. This same law stated that it would begin to apply to residential projects 12 months after the approval of the regulation that establishes the procedure, requirements, and conditions for granting energy ratings and preliminary ratings and their advertising, which should have been done in February 2022. However, the Ministry of Housing and Urban Planning (MINVU, in Spanish) has yet to issue this regulation. Article 3 of the EEL provides in its final paragraph that "all of the above is understood, notwithstanding the faculty of any natural or legal person, to request the energy rating and preliminary rating following current legal regulations." Thus, energy labeling is currently voluntary for housing.

According to the EEL, homes built before 2000 (which, therefore, do not have any thermal requirements) will be rated with the letter G; homes that meet the requirements for roofs with an F, and those that observe the provisions applicable to roofs, walls and ventilated floors, with an E; i.e., those that comply with the current TR. Finally, homes with adequate savings and environmental quality will be rated with the letters C and D, and homes with a high energy efficiency purpose will be rated with A and B. As can be seen, the letters A, B, C, and D can only be assigned to homes that are more energy-efficient than the current building standard (Figure 1).

It is important to remember that the letters are referential, and there are energy savings ranges between letters. Thus, obtaining a good energy rating will require a set of factors. The rating obtained will also be influenced, for example, by the house's orientation and, consequently, the exposure to solar radiation. Hence, two houses can have the same construction standards but different energy performances due to their orientation.

The energy rating required by the EEL seeks to inform consumers about the property's energy costs before purchasing by granting an energy efficiency label and a rating report. The label

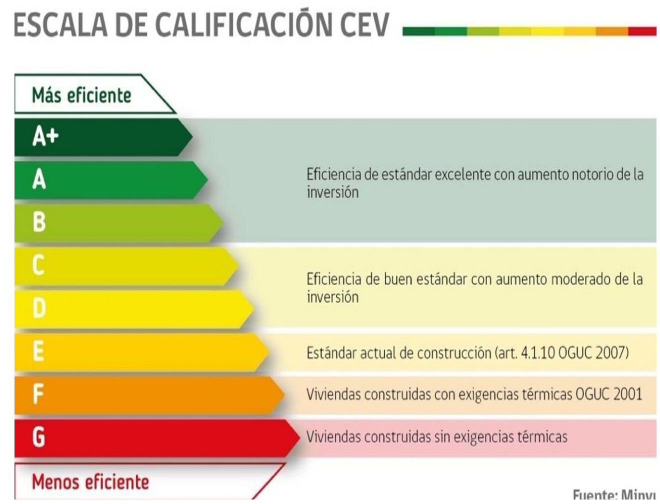

Figure 1. CEV rating scale. Source: Minvu (2019).

provides summarized information on the energy performance of the evaluated home, a preliminary rating, and another for the energy rating of the homes (CEV Manual, 2019). There is also an Energy Efficiency Seal (Figure 2) that shows the primary energy efficiency indicators of the dwelling or the housing complex; in the latter, said seal will consider a weighted percentage of the energy savings (CEV Manual, 2019).

THE ADVERTISING OF THE REAL ESTATE PROJECT AS AN INTEGRAL PART OF THE PURCHASE AND SALE CONTRACT

Advertising often describes housing projects as energy efficient, which is attractive to consumers because of the savings it entails. It is worth asking if such statements are included in the sales contract and, as such, if the consumer can sue for their breach.

Article 1 N°4 of the PCRL (regulation of article 18 paragraph 7 of DFL N°458, of 1976, approving the Law on Urban Planning and Construction [LGUC]) states that advertising has an objective side aimed at informing consumers and a subjective side aimed at persuading them to make the final decision to acquire the advertised good. Only the objective side of advertising is included in the sales contract and can be demanded by consumers (Momberg, 2007; De la Maza, 2013a).

To determine whether advertising claims about energy efficiency without any scientific support belong to the objective side (and, consequently, are included in the contract), it must be kept in mind that the basis of advertising is the protection "of the legitimate expectation of reasonable

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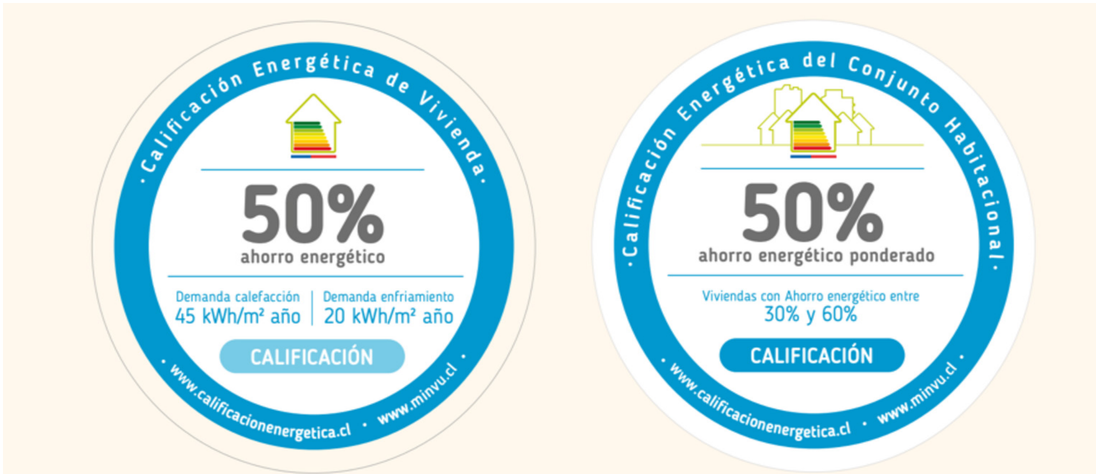

Figure 2. Energy Efficiency Seal. Source: CEV Manual (2019), pp. 59-60.

expectations that the consumer has formed regarding expressions that, pre-contractually, the offerer has issued" (Isler, 2020). The key is in protecting that trust (López, 2019). That is to say, advertising information that the average consumer can reasonably rely on must be included in the contract (De la Maza, 2013b), meaning by such, those intrinsically vulnerable subjects who are unable to properly and promptly process the information that is available on the market (Isler, 2011). In conclusion, those plausible conditions for an average consumer should be respected (Isler, 2020).

However, as analyzed in this research, the following aspects must also be considered: 1) advertising usually describes specific attributes to which, given their characteristics, they attribute the benefit of producing energy savings; 2) many of these attributes have a complex or challenging to understand operation; for example, double-coated walls, high-performance thermal envelope, EIFS system, high-efficiency ventilation, convective ventilation, among others; 3) in most cases, the consumer will only be able to corroborate if they actually produce the promised savings after a while; in fact, in many situations it will be very difficult to confirm; 4) faced with the lack of understanding or available information, consumers often turn to "brand personality" as an alternative source of information (Sander et al., 2021; Aaker, 1997 and; Freling & Forbes, 2005), which plays a vital role in the ad's credibility (Sanders et al., 2021, p. 436) and, 5) most real estate projects are bought off-plan; i.e., whose construction is not completed and, therefore, do not have the definitive reception (Caprile, 2008). In these cases, consumers cannot review the property's attributes or operation, as the showhouse or apartment may not be ready.

Accordingly, it is argued that such expressions generate reasonable trust in consumers, who can consequently sue based on breach of the advertising.

GREENWASHING AS A PARTICULAR TYPE OF MISLEADING ADVERTISING AND NON-COMPLIANCE WITH THE DUTIES OF INFORMATION

Law N°19.496 of 2019, in article 28 of the PRCL, provides that "he infringes the provisions of the law, who, knowingly or should have known and, through any type of advertising message, induces error or deception regarding certain characteristics and conditions of the product that are described in each of its sections." Specifically, its letter f) alludes to the condition of not causing damage to the environment and quality of life. Although the PRCL does not expressly talk about greenwashing, it does recognize the behavior, configuring a particular hypothesis of misleading advertising (Fernández, 2021). However, the regulation does not cover all manifestations of this behavior.

In this sense, on May 31st, 2022, a draft bill was presented that, according to Article 1, aims to prevent, regulate, and punish greenwashing (Bulletin N°15.044-12, 2022). Article 2 defines the figure but also enshrines other relevant concepts. One is "sustainability advertising," which is essential to understand greenwashing. According to the standard, this consists of "all advertising communicating responsible and sustainable practices of companies, their brands, products, and services." Likewise, Article 2 letter b) defines "greenwashing" as "Sustainability advertising carried out in contravention of the provisions of this law." As can be seen, it is an open standard that requires content on a case-by-case basis.

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The bill also seeks to replace the aforementioned article 28 letter f) of Law N°19.496 (Isler, 2020). According to the proposal, the supplier of a product commits an infringement that, through advertising, induces error or deception regarding: "Its condition of not causing harm to the environment or the quality of life or of having characteristics that are explicitly or implicitly stated as beneficial to the environment ...". If the proposal is compared with the current standard, it is possible to notice that the latter, at least literally, omits that assumption contemplated in the bill that consists of advertising characteristics of the product as beneficial for the environment and people when, really, they are not. This is precisely what happens when the supplier attributes energy efficiency to the dwelling because, in some way, he is signaling that it will collaborate in reducing the carbon footprint when it is not so.

When the error or deception is related to a home's energy efficiency, the conduct is also related to letter c) of the aforementioned law (Isler, 2020), which refers to "the relevant characteristics of the good or service highlighted by the advertiser or that must be provided following the commercial information standards." Obtaining a direct benefit with the purchase of the house, consisting of saving money because of the decrease in energy expenditure, is a relevant characteristic that influences the purchase decision. However, the bill is currently being processed (first constitutional procedure).

Thus, given that there is little regulation on greenwashing currently, several actors have proposed rules on the matter. An example of this is the "Green Communication Guide" - a document prepared in 2014 by Fundacion Chile in collaboration with diverse actors such as Sernac, the Council of Self-Regulation and Advertising Ethics, and the Ministry of the Environment. The document talks about the "seven sins of greenwashing." When analyzing housing advertising, it is possible to highlight two "sins"[2]. The first is "the lack of evidence," which refers to assumptions about the environmental attributes communicated that cannot be corroborated by reliable information or certifications. In this sense, the Code of Advertising Ethics of the Council of Self-Regulation and Advertising Ethics (CONAR) provides that assertions of the type "compatible with the environment," "ecologically safe," "green," "sustainable" or any other that suggests that the product does not impact the environment or only does so positively, must have a clear demonstration that supports them (Article 27).

On the other hand, the PCRL enshrines "the right to truthful and prompt information about the goods and services offered, their price, contracting conditions, and other relevant characteristics thereof ..." (Article 3 letter b). The provider then must provide such information. In this part, it should not be forgotten that real estate companies and construction companies engaged in selling real estate are suppliers under the law. The International Organization of Consumer Unions (IOCU), referring to the comparative experience, states that an educated and informed consumer has a more regular behavior in the market. Any decision-making requires as much information as possible. Although the generation of information always has a cost, the consumer will be willing to pay it to the extent that it benefits him (Barrientos, 2024). However, it is warned that there is no fundamental knowledge of what the energy efficiency of a house implies, what the CEV consists of, or other instruments in the field of sustainable construction (Jiménez *et al.*, 2023). In general, it is seen that there are also no campaigns led by the Ministry of Housing and Urban Planning, the Ministry of Energy, Sernac, or any consumer association aimed at educating consumers on these matters.

Under Article 3, paragraph 3 of the EEL, the energy efficiency label and report must be included in the project's advertising. According to this law, both constitute basic commercial information defined in Article 1° N°3 of the PCRL as "the information, instructions, background information, or indications that the supplier must compulsorily provide to the

2 The remaining sins are as follows: 3) *Sin of Vagueness*: This consists of the vagueness used when mentioning the environmental attributes of the respective product, which can confuse the consumer; 4) *Sin of irrelevance*: minimum requirements required by law are mentioned as attributes; 5) *Sin of the lesser of two evils*: This occurs when, for example, a specific company says it is a leader concerning its competence in caring for the environment, but due to the nature of the product, it has an important environmental or social impact. For example, organic cigarettes and; 6) *Sin of fibbing*: The company proclaims itself as green under false arguments; for example, it alludes to some certification it does not have. Sin of the hidden trade-off that consists of advertising based on a group of attributes but leaves aside others that may have the same or greater environmental and social impact. Source: Green Communication Guide, 2014, p. 21.

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consumer, in compliance with a legal regulation." This highlights the importance that the legislator attaches to the labeling content and the respective energy efficiency report.

However, beyond the express consecration of this duty in the EEL and the lack of a regulation that can make it operational, the truth is that the PCRL imposes the duty to inform, and establishes the standards that such information has to meet. This leads to the conclusion that information regarding energy efficiency should be provided. However, it is observed that, in general, real estate and construction companies that voluntarily submit to the energy efficiency rating do not transmit the implications of the rating obtained. Therefore, it is hardly likely to be understood by consumers. It is not just any information but rather highly complex information; consequently, it is a real challenge to establish how it should be made known to consumers for their proper understanding. The respective regulation must solve this problem.

It should be noted that Article 3 of Law No. 19.496 of 2019 aims to prevent, regulate, and punish greenwashing; it also reiterates and specifies specific information duties established in the PCRL. Thus, "companies that advertise sustainability must provide complete, truthful, verifiable, understandable, and accurate information and may not omit relevant background information that may mislead." If this law is passed, the scope of this duty in light of the PCRL will need to be determined in each case. At the same time, it establishes that companies that advertise sustainability must keep information about their environmental practices available, accessible, and permanently updated on their websites.

RESULTS OBTAINED FROM STUDYING THE ADVERTISING OF REAL ESTATE PROJECTS ON SALE

The advertising of 45 real estate projects offered for sale in the municipality of Santiago during June 2024, disseminated through the websites of the real

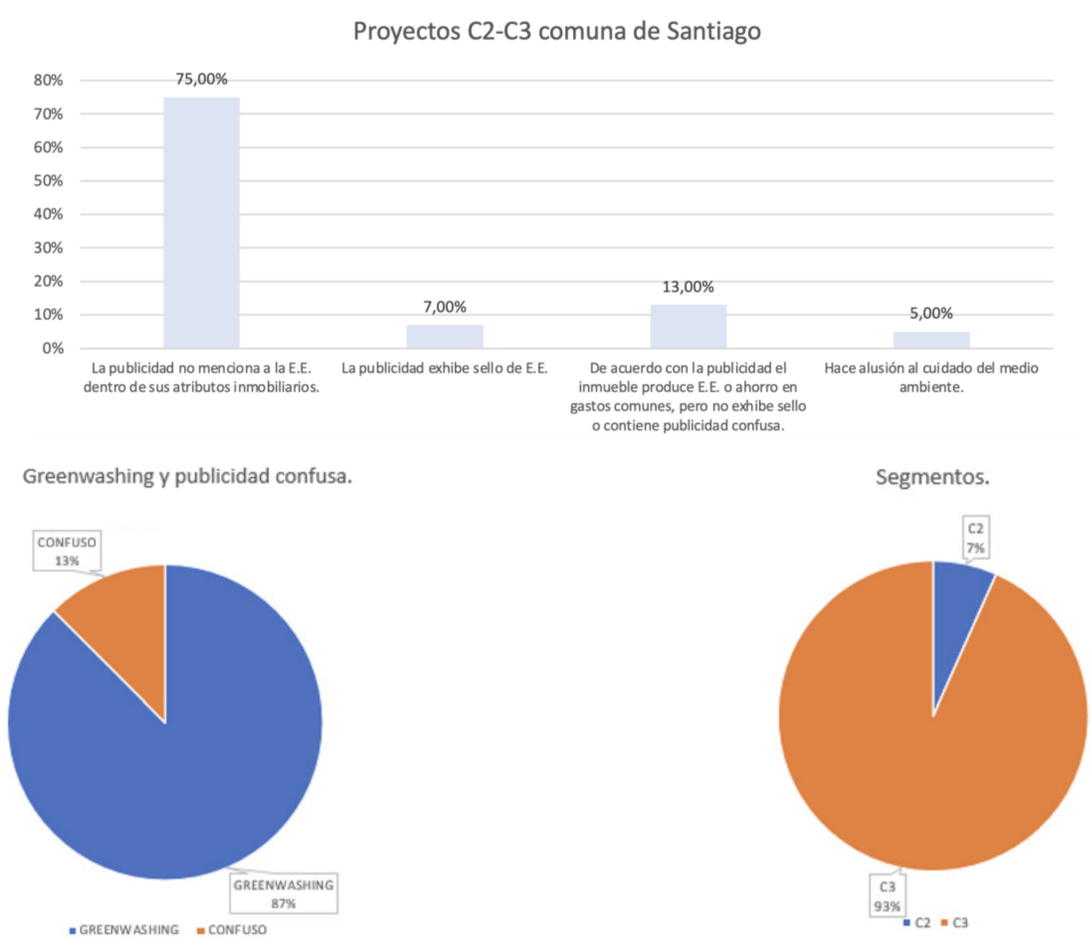

Figure 3. Results obtained from the analysis of the advertising disseminated in 45 real estate projects located in the municipality of Santiago related to energy efficiency. Source: Preparation by the Author.

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estate or construction companies, was reviewed. The prices of all projects range from 2000 to 4000 UF (Development Units). The advertising for the dwelling's energy efficiency was examined using the PCRL.

An overview of the advertising on energy efficiency made for the real estate projects on sale and the information consumers have in this matter is provided below. The advertising analyzed was divided using the following criteria: a) one that does not mention energy efficiency (EE) as one of its attributes focusing on other amenities; b) one that exhibits an energy rating seal (ER) whether it is the one given by the Ministry of Housing and Urbanism or another entity; c) advertising that offers energy efficiency or savings in administrative fees within its attributes without exhibiting an EE seal or a specific rating without the possibility of knowing whether the project has undergone some rating process and, d) one that alludes to the care of the environment and sustainability. Subsequently, considering the prices of the units for sale, the socio-economic sector to which it was aimed was established, and a distinction was made between the sales methods used (buy off-plan, during construction, or with immediate delivery). This panorama is presented through the following graphs (Figure 3).

As can be seen, the advertising for 34 projects (75%) does not reference energy efficiency, energy savings, cost reduction, or environmental care. It is possible that this is not only due to the voluntariness of energy labeling but also to the fact that consumers are unaware of what it means. Therefore, middle-class consumers belonging to the social categorization segments C2 and C3, considered in the values of the units for sale, seem to value other attributes or characteristics such as connectivity, the equipment of shared spaces, and even special spaces for pets. Consequently, in all these cases, there is a lack of information that is relevant when making the purchase decision; however, this is not noticed by consumers due to the scarce information available and the absence of plans or programs aimed at educating consumers in these matters.

The study showed that only three of the 45 evaluated real estate projects, equivalent to 7%, were subjected to the energy rating process. However, in most cases, the explanation of what the rating obtained means or its implications is omitted. In fact, only one of the projects had more detailed information on this point.

On the other hand, the advertising of 6 projects reviewed (13%) can be qualified as greenwashing because it affirms that the project or its units are efficient or produce energy savings and, with it, a decrease in heating costs or administrative fees. However, it does not exhibit the CEV or any other type of certification or scientific support that allows corroborating such claims. In this way, even though energy labeling is voluntary, the truth is that advertising for such projects does not comply with the rules included in the PCRL and the information duties required of real estate and construction companies in their capacity as "suppliers." It should be noted that, in accordance with Article 24 of the PCRL, misleading advertising incurs a fine for the offender of up to 1500 UTM (Monthly Tax Units). The regulation adds that if such advertising affects product qualities that affect the environment, a fine of up to 2250 UTM may be imposed. If the bill that aims to regulate greenwashing is approved, such fines will be considerably higher. However, it is not always easy to notice that practices of this type are used.

During this research, an advertisement classified as "confusing" was identified because, although it does not expressly talk about "energy efficiency" or "savings," it refers to more comfortable environments throughout the year or to homes capable of maintaining pleasant temperature standards or thermal comfort, which is usually done after mentioning specific real estate attributes related to thermal insulation. In these cases, it is possible that the consumer deduces from these statements that the house is efficient or will imply a saving in energy expenditure and, therefore, its costs. However, the qualification of "misleading" advertising is more debatable. Advertising for one of the six mentioned projects has these characteristics.

The advertising of only two projects somehow alludes to the care of the environment. This number is consistent with the study's results above, as it reflects that consumers, as a rule, are not so interested in the possibility of reducing the carbon footprint or the ecological character that housing may have.

CONCLUSIONS

In practice, the voluntariness of energy labeling translates into a lack of available information on energy efficiency, incomplete information, or information provided without scientific support, thus favoring practices such as greenwashing. Such misinformation leaves consumers disadvantaged, preventing them from making a purchase decision that best fits their needs and interests.

Under the EEL, the information in the energy rating report must include the advertising for the real estate project; therefore, establishing how this should be made known to consumers for their proper understanding, especially considering its complexity and highly technical nature, is still pending. This must be accompanied by training or compliance plans for real estate and construction companies and educational plans focused on consumers.

The current regulations that regulate misleading advertising allow fining for tax benefit the supplier that resorts to these when offering their products and, simultaneously, allow consumers who are victims of such practices to sue civilly for breach of the advertising conditions once the harm has been suffered. In this sense, the draft bill that seeks to regulate greenwashing increases the applicable fines and specifies specific information duties. However, there are no preventive controls to protect consumers against these behaviors and, consequently, allow them to have the proper information before purchasing a home. In this way, the real estate consumer can only be adequately protected when the energy rating is mandatory and with the same criteria. As long as this does not happen, they will continue to be exposed to this type of practice and purchase decisions without having relevant information.

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PREFABRICATED WOODEN HOUSING QUALIFICATION BASED ON REGULATORY COMPLIANCE, COMPLEXITY, AND SUSTAINABILITY IN CENTRAL CHILE

CALIFICACIÓN DE VIVIENDAS PREFABRICADAS EN MADERA BASADA EN ATRIBUTOS DE CUMPLIMIENTO NORMATIVO, COMPLEJIDAD Y SUSTENTABILIDAD EN CHILE CENTRAL

CLASSIFICAÇÃO DE MORADIAS PRÉ-FABRICADAS DE MADEIRA COM BASE EM ATRIBUTOS DE CONFORMIDADE REGULATÓRIA, COMPLEXIDADE E SUSTENTABILIDADE NA REGIÃO CENTRAL DO CHILE

Rose Marie Garay-Moena
Magister en Ciencias e Industrias de la Madera
Académica, profesora asociada, Facultad de Ciencias Forestales y de la Conservación de la Naturaleza
Universidad de Chile, Santiago, Chile
https://orcid.org/0000-0002-7662-9724
rgaray@uchile.cl (Autora de Correspondencia)

Susana Graciela Benedetti-Ruiz
Licenciada Ciencias Forestales
Directora de proyectos
Instituto Forestal, Santiago, Chile
https://orcid.org/0009-0000-2217-3568
sbenedet@infor.cl

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RESUMEN

El estudio revisa los antecedentes publicados por fabricantes de viviendas prefabricadas en madera en Chile central. La metodología indaga en medios digitales de venta y servicio de impuestos internos. Utiliza los atributos de cumplimiento normativo-técnico, complejidad y sustentabilidad para calificar las viviendas prefabricadas en las regiones de Valparaíso, O'Higgins y Metropolitana. Un 83% de empresas son "constructoras-fabricantes", 83% están legalmente constituidas. La complejidad revela que, para proyectos de mayor envergadura, 54% tienen nivel bajo, 35% nivel medio y 11% nivel alto. Hay debilidades en cumplimientos normativos y en información técnica para los potenciales clientes, siendo la sustentabilidad el atributo menos destacado, ya que pocas explicitan datos como huella de carbono, reciclaje de materiales o certificaciones voluntarias para diferenciarse en el mercado. Por tanto, se concluye que faltan acciones para potenciar a este sector productivo, con potencial de industrialización, incorporando gestión y reglamentación, con lo que disminuiría la inseguridad territorial por autoconstrucción.

Palabras clave
viviendas de madera, ventas por internet, seguridad, sustentabilidad

ABSTRACT

This study reviews the background information published by manufacturers of prefabricated wooden housing in central Chile. The methodology carries out the investigation using digital sales and internal tax service media. It uses regulatory-technical compliance, complexity, and sustainability to rate prefabricated homes in Chile's Valparaíso, O'Higgins, and Metropolitan regions. 83% of the companies are "construction-manufacturers", while 83% are legally constituted. As for complexity, it is revealed that, for larger projects, 54% have a low level, 35% have a medium level, and 11% have a high level. There are weaknesses in regulatory compliance and in technical information for potential clients, with sustainability being the least prominent attribute, as few explain data such as carbon footprint, recycling of materials, or voluntary certifications to differentiate themselves in the market. It is concluded that there is a lack of actions to strengthen this productive sector, which has industrialization potential, by incorporating management and regulation, which would reduce the territorial insecurity for self-construction.

Keywords
wooden homes, online sales, safety, sustainability

RESUMO

O estudo analisa as informações publicadas pelos fabricantes de casas de madeira pré-fabricadas na região central do Chile. A metodologia explora os meios de vendas digitais e o sistema tributário nacional. Ela usa os atributos de conformidade técnico-regulatória, complexidade e sustentabilidade para classificar as casas pré-fabricadas nas regiões de Valparaíso, O'Higgins e Metropolitana. 83% das empresas são "construtoras-fabricantes e 83% são legalmente constituídas. A análise revela que, no caso dos projetos maiores, 54% têm um nível baixo, 35% um nível médio e 11% um nível alto. Há deficiências na conformidade regulatória e nas informações técnicas para clientes potenciais, sendo a sustentabilidade o atributo de menor destaque, pois poucas empresas fornecem dados como pegada de carbono, reciclagem de materiais ou certificações voluntárias para se diferenciar no mercado. Conclui-se, portanto, que faltam ações para aprimorar esse setor produtivo, com potencial de industrialização, incorporando gestão e regulamentação, o que reduziria a insegurança territorial decorrente da autoconstrução.

Palavras-chave:
casas de madeira, vendas pela internet, segurança, sustentabilidade.

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INTRODUCTION

VULNERABILITY FACTORS THAT INTERACT IN THE FACE OF DISASTERS

The housing deficit caused by market problems, the lack of supply caused by disasters, and the proliferation of constructive solutions with different levels of quality are closely linked. While the State tries to solve housing needs, new needs are continuously generated in an endless cycle, and only some solutions are being regulated to ensure habitability that provides a lasting solution.

Actions are required throughout the risk cycle, ideally before an event, to prevent extreme natural events from becoming disasters (UNDRR, 2015). This entails allocating time to plan and provide resources for actions that reduce or avoid increased risks (Lacambra *et al.*, 2015) and contribute to mitigation, preparedness, response, or recovery. In this sense, having clarity about who the population at risk is and where it is located helps to make decisions to reduce the impact of future events and generate more resilient communities. In Chile, this has been institutionalized in Law No. 21,364 of 2021, which establishes the National Disaster Prevention and Response System, creating the National Disaster Prevention and Response Service (SENAPRED, in Spanish). This regulation focuses on prevention. However, among the pending needs, the management of housing supply to achieve timely and effective responses still needs to be implemented operationally. For example, this entity's responsibility is to ensure the supply of emergency housing as regulated by Exempt Res. 1448 (BCN, 2023c), which, albeit provisional, has direct implications for definitive solutions that do reduce the housing deficit. In this sense, the prefabricated wood construction industry, presented in the following article, offers an alternative.

Given how some of the prefabricated houses in Chile are installed and used, it is vital to have territorial planning instruments that include risk areas. Nevertheless, in municipalities that do not have the resources to implement more overarching plans, the lives of people who must be preventively evacuated from risk areas are usually affected. An example of this is the urban sprawl in areas exposed to the threat of forest fires, which is not explicitly considered in the Urban Planning and Construction Ordinance (OGUC, 2017 in Spanish), according to the article that defines "non-buildable zones" and "risk areas" (Article 2.1.17). To look for comprehensive solutions, some Communal Regulatory Plans (PRC, in Spanish) and ordinances include forest fires and implement measures such as distancing, firebreaks, water networks, the removal of fuels and flammable materials, and changing to fire-resistant finishes of no less than an F-180 classification (González-Mathiesen & March, 2023). Meanwhile, the Draft Law that the National Forest Service prepared, in Article N°3, defines forest urban interface areas. It establishes that these must be identified in Regional Land Use Planning and Intercommunal and Communal Regulatory Plans, although it is still weak in preventive measures for existing buildings. The purpose of noting this issue in this article is because these areas are where prefabricated housing is commonplace, and it is urgent to reflect on changes in public policy with a global and systemic view on how to adapt living to climate change, which not only depends on each municipality in its territory but must be promoted nationwide.

HOUSING SHORTAGE

Analyzing each region (Table 1) provides greater clarity about the situation. If this is linked to the research results on the different opportunities the market offers to meet the needs, a virtuous circle could be generated instead of a vicious one.

The quantitative deficit calculated with the 2022 Casen Survey, conducted by Chile's Ministry of Social Development and Family (MDSF, 2024), amounts to 552,046 new homes left to be built. The regions with the highest number of households with affordability

Table 1. Housing situation by region. Source: Prepared by the authors with data obtained from the 2023 Regional Report (BCN, 2023d)

O'Higgins	Metropolitan	Valparaiso
1.03 million inhabitants (projected to 2024), surface area 16,387 km^2	8,420,729 inhabitants (projected to 2024), surface area 15,403.2 km^2	2,025,693 inhabitants (projected to 2024), surface area* 16,396.1 km^2
Total n° of dwellings 354,324 (99,909 rural). Housing deficit. 21,980 housing units	Total N° of dwellings 2,378,490 (92,339 rural). Housing deficit 504,770 homes	Total N° of Dwellings 788,830 (79,618 rural). The housing deficit without encampments is 102,000 dwellings; with encampments (255), there are 136,000 dwellings. Dwellings affected by the recent fire of January 2024: 8,188

* Surface Area of Continental Chile: 756 770 km22

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problems in 2022 are the country's most populous regions: Metropolitan (504,770 households) and Valparaíso (90,043). While the regional distribution of households in encampments, according to the 2022 List made by the Ministry of Housing and Urbanism, MINVU (2023) in Spanish, shows that the most significant number is located in the Valparaíso (25.6%) and Metropolitan (18.6%) Regions.

WOOD CONSTRUCTION PRODUCTION CAPACITY

Although there is no survey of prefabricated wooden housing construction capacities, since no Chilean public or private body is responsible for doing so, it is a matter of observing the materiality with which emergency, temporary, cabin-type second homes, and modular homes are implemented to perceive that the demand exists and, therefore, the supply is increasing.

The analysis of used dwellings addressed by INFOR (2021) for 68,466 of them located in all regions of the country, using data from the 2017 Casen survey (Ministerio de Desarrollo Social y familiar, 2018), indicates that 38.1% are built mainly using wood, albeit always as a lower quality option throughout the size ranges, and worse still in segments under than 40 m^2; since for every 100 wooden houses in the country, 23 have less than 40 m^2. At the same time, there are 12 and 13 units in brick and concrete, respectively. The data shows that materiality is related to families' poverty level and the house's size.

Wood is the most commonly used material for homes of different socio-economic strata (Harju, 2022; Hidalgo et al., 2022), for being "the sustainable solution of the future in buildings in the world" (Green & Taggart, 2020; Bascuñán, 2021; Pacini, 2021; Garay *et al.*, 2022), and more affordable in rural areas due to availability and poor access to state subsidies (González Méndez, 2022). Mistakenly, costs are reduced by supplying the market with homes that do not have sustainability attributes, such as energy efficiency and a low carbon footprint, from their manufacturing. In this sense, the thermal insulation of dwellings is mandatory.

Self-builds and housing assembly on the same site generate overcrowding (Hidalgo *et al.*, 2022; González Méndez, 2022; Martínez Gamboa, 2022). The private market offers diverse construction typologies, qualities, and delivery times, from assembly kits to complete turnkey installation services. The question is who controls and supervises their correct installation, while the final reception of the work does not always occur.

Among the suppliers are consolidated architectural offices and/or construction companies, which comply with regulated technical specifications (TS) and even cover the final reception of the work. In other cases, only substandard habitability is accessed, where sustainability and safety indicators rarely exist or are valued (Garay *et al.*, 2021a). Since construction using materials such as brick and concrete generates 35% of waste globally, consumes 20% of water, and emits almost 40% of greenhouse gases, sustainability should not be optional since wood construction is being faced efficiently worldwide. To encourage this process of adopting sustainable construction in Chile, the work of the International Living Future Institute has been taken as an example. In 2006, the Institute launched the world's most rigorous and sustainable green construction program: the Living Building Challenge. Thus, 20 buildings globally aspire to achieve a "Net Zero Energy Building" (NZEB) certification (ILFI, 2024; Madera 21, 2023). Until now, structural construction in wood has not had access to high-rise buildings, except for some buildings created with a demonstrative effect or corporate buildings, having an excellent possibility for growth. (Ugarte *et al*, 2018; Wenzel & Guindos, 2024).

The study investigates the attributes of regulatory-technical compliance, complexity, and sustainability that prefabricated housing manufacturers offer through digital media. This allows understanding how potential customers receive information and suggesting improvements.

METHODOLOGY

Bibliographic material of a scientific-technical nature, available in digital format, was obtained from the databases of books and journals subscribed to by the University of Chile, such as Web of Science, Scopus, ScienceDirect, and Springer. Literature and information resources from the Google Scholar search engine were also obtained, which provided context to the importance of the study and the state of the art. These bibliographic documents were stored in the Mendeley bibliographic manager. To create a list of the products, a search with Spanish keywords was conducted using Instagram, Facebook, LinkedIn, Instagram, and Google. The next step was to verify the company's formal existence in the Internal Revenue Service (SII), georeferencing their location, verifying their taxpayer identification number, and checking that the contact details were authentic. This generated a registry that included 88 companies, eliminating only those that did not have formal information.

Exhaustively reviewing digital sources for bibliometrics and descriptively analyzing the national market products classified as houses, prefabricated, or modular wooden houses was relevant. These were entered into the database search engines accompanied by Boolean operators to generate different combinations. This database generated a record in the Microsoft Excel software, where information on prefabricated housing

Table 2. Attributes (Complexity, Regulatory Compliance, Sustainability) and Likert scale. Source: Preparation by the authors.

Attribute	Variables	Level of the variable	Scale
I: Complexity	A: Experience of the manufacturer or construction company	Not mentioned	1
		<5 years	2
		5-15 years	3
		16-25 years	4
		<25 years	5
	B: Diversity of the offer: N°, design, and sophistication of the models	Not mentioned	1
		<5	2
		5-10	3
		11-15	4
		>15	5
	C: Diversity of housing sizes	Not mentioned	1
		<40m²	2
		40-72m²	3
		73-120m²	4
		>120m² or tailored	5
	D: Formality, initiation of activities, and registration with the Internal Revenue Service	Informal	1
		Formal	5
	E: Possibility of sale with State-granted housing subsidy	No	1
		Yes	5
	F: Participation in framework agreements, public tenders, and/or integration into real estate management	No	1
		Yes	5
II: Compliance with current regulations (CNV)	A: Seismic resistance	No	1
		Yes	5
	B: Fire-resistance	No	1
		Yes	5
	C: Thermal comfort	No	1
		Yes	5
	D: Acoustic comfort	No	1
		Yes	5
	E: Minimum dimensions	No	1
		Yes	5
	F: Water tightness	No	1
		Yes	5
	G: Airtightness	No	1
		Yes	5
	I: Protection of materials for their durability	No	1
		Yes	5

Attribute	Variables	Level of the variable	Scale
III: Sustainability	A: Structural materiality of the building	Not mentioned	1
		Hybrid	3
		Wood	5
	B: Risk Reduction - forest fires, earthquakes, climate change.	Not mentioned	1
		At least one	3
		Two or more	5
	C: Bioeconomy - Reduce-Reuse-Recycle (RRR)	Not mentioned	1
		At least one	3
		Two or more	5
	D: Energy efficiency, water, self-generation, reuse	Not mentioned	1
		At least one	3
		Two or more	5
	E: Others of the voluntary sustainable construction code (MINVU, 2023)	No	1
		Yes	5

manufacturers was compiled for the three regions analyzed.

After identifying the companies, the products offered were analyzed using the attributes and variables indicated in Table 2 as a guide. The study characterized "prefabricated housing" of 88 legally constituted manufacturing companies operating in Chile's O'Higgins, Valparaíso, and Metropolitan regions. The analysis is based on their explicit descriptions of their products and the observation of images they show as unequivocal evidence of some attributes. This strategy allowed identifying the wooden housing products available in the national market and described the variables to be observed for the complexity, regulatory-technical compliance, and sustainability attributes.

With the information collected, a digital directory of the companies was created, and the housing models offered were selected and rated considering the attributes and variables detailed in Table 2; there was a range of more than three models; the three most representative ones were chosen to narrow down the list and the rating calculation. In this way, a rating score is a number acquired jointly for all the products in a company, considering the number of attributes observed (unweighted), presented on a Likert scale of 1 to 5, 1 being the lowest and 5 the highest. These levels are described in Table 3.

The rating is based on three criteria: (1) Complexity (C); (2) Compliance with current regulations (CNV); and (3) sustainability (S). The complexity attribute, C, involves the manufacturer's experience and the diversity of its products

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Table 3. Indicator guidelines based on attributes, according to quantity and quality, expressed on a Likert scale. Source: Preparation by the authors.

Quality of attributes (based on Table 1)	Description and number of attributes for each product (minimum one, maximum three per company, selected from the models offered)	Scale.
Not mentioned	It does not mention information about the characteristics despite being a formal company. It does not mention CNV in its products. Without sustainability information. Products without images in digital media. Low complexity: no experience or not indicated, no sales through tenders or subsidy, no description of technology and/or certification	1
Attributes without differentiating	Mentions only one of these characteristics: dimensions and number of available models. States CNV in thermal and/or acoustic comfort, seismic, or fire resistance. Provides some sustainability information. It is possible to determine the complexity level through the published models and projects. Belongs to this level only if it reaches average complexity. Formal company, evidence of the use of technology in its products, displays images and describes technically available models. It does not indicate subsidized sales or having certifications	2
Clearly identifiable attributes	Mentions two to four characteristics: dimensions and number of available models. States CNV in thermal and acoustic comfort, seismic, or fire resistance. Provides some sustainability information. It is possible to determine the complexity level through the published models and projects. Belongs to this level only if it reaches average complexity. Formal company, uses technology, displays images and description of available models. It does not indicate subsidized sales or having certifications.	3
Attributes with relevant technical explanation	Mentions three to five characteristics: dimensions and number of available models: States CNV in thermal and acoustic comfort, seismic, or fire resistance. It stands out through the sustainability information. It describes the products in suitable technical detail and presents plans and construction material sheets. It is possible to differentiate the ability to develop projects and products of greater complexity and flexibility that are adjustable to customer needs. It includes sustainability issues connecting with current needs. This group belongs to those that DITEC has registered as Industrializers.	4
Significantly outstanding attributes	Mentions more than five of these characteristics: dimensions and several available models. States CNV in thermal and acoustic comfort, seismic, or fire resistance. It stands out through the sustainability information. Formal company, uses the highest technology available in the country, displays images and description of available models. Indicates sales with subsidies, has some certification, and has an outstanding level in international sustainability indicators	5

in terms of types, models, sizes, product presentation, and company experience. It also involves formality, acceptance of subsidies, participation in a framework agreement, and after-sales services of the product. The CNV is based on the products explicitly demonstrating compliance with relevant technical standards, such as the variables detailed in Table 2, which are linked to aspects related to durability, particularly behavior for earthquakes and fires, as included in the OGUC. Finally, the Sustainability attribute, S, refers to variables that stand out regarding the standards and certifications adopted, such as the carbon footprint measurement, life cycle analysis, bioeconomy, process quality, efficiency and innovation, and improved acoustic and thermal characteristics of dwellings beyond the CNV.

The information register incorporates and describes the presence or absence of this information for the dwellings offered, as well as their details and relevant explanations.

The rating process was simplified by averaging the three attributes equally. This aspect is clarified because the indicator model published by Garay *et al.* (2022) was considered, where a greater or lesser weighting of one attribute compared to the others was taken into account, considering a complex multicriteria matrix.

Table 3 presents the indicator guidelines, grouping the variables of each attribute considered in Table 1 (complexity, regulatory compliance, sustainability) on a Likert scale from 1 to 5.

Table 4: Evaluated prefabricated houses and Likert scale level by region. Source: Preparation by the authors.

Region	Qualified companies*	Number of companies by Likert scale level	Score.
Valparaiso	***16***	1	1
		7	2
		8	3
Metropolitan	***61***	5	1
		29	2
		23	3
		4	4
O'Higgins	***10***	2	1
		4	2
		4	3

*The number of rated products was between 1 and 3

RESULTS AND DISCUSSION

Table 4 shows the units evaluated by the types of prefabricated houses located on each Likert scale achieved for each region.

According to what has been observed, the prefabricated housing industry is characterized by an average level of complexity; i.e., most companies can produce dwellings

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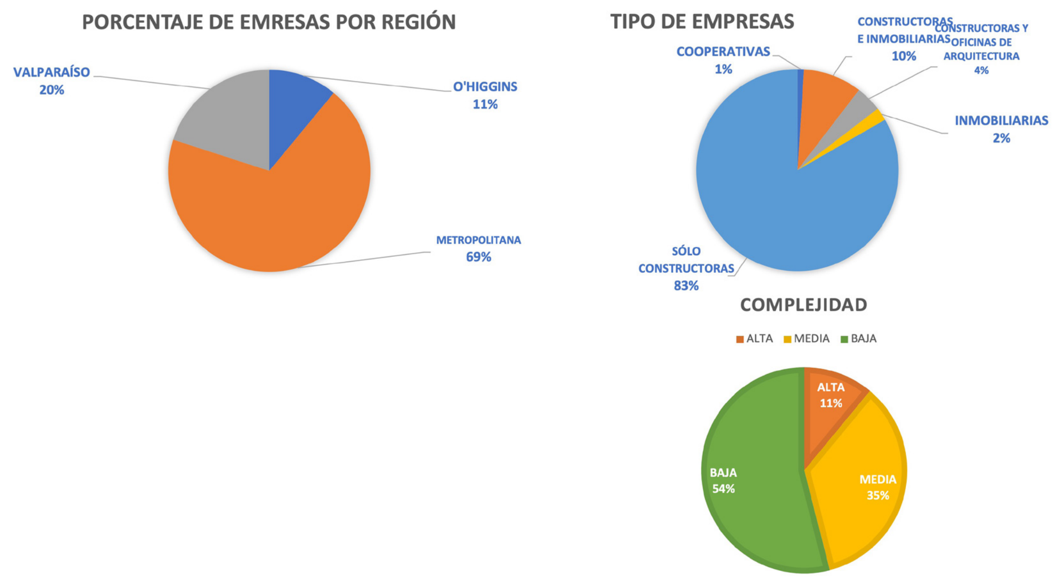

Figure 1. Evaluation of "Prefabricated Houses" Products for the three regions. Source: Preparation by the authors.

with standards that fit the requirements. However, this offer is not privileged since there is only sometimes an obligation to demonstrate technical compliance. This is ignored under the buyer's agreement, possibly to reduce costs and difficulties associated with the installation. In addition, the study shows that there is a sale of an assembly kit or the assembled house, but without installation, so that users can take it. In this way, the house manufacturer is dedicated to manufacturing and does not always assume responsibility for the installation. Therefore, it is the buyer's responsibility if rules are transgressed or mistakes are made. It must be considered that the work's final reception might be made or not, as municipal work directions use only the documents presented and not onsite inspections for approval (Garay *et al.*, 2021b; INE, 2023; Quinzacara, 2021; BCN, 2023b).

There is a significant group of companies that obtain a low rating, which is worrisome when the current housing deficit scenario leads people to look for urgent and low-cost solutions, finding in this market an option to temporarily and precariously solve housing needs, forming a vicious circle of dissatisfaction and demand for definitive solutions, where temporary housing becomes the "normality." The result is larger encampments or overcrowding by installing additional housing in a space initially intended for a single house. In this regard, it should be noted that, since November 2023, through Exempt Resolution 1448, those who provide emergency housing are obliged to comply with minimum standards (BCN, 2023c). Consequently, it is expected that homes built in the country will soon meet the standards for their location and that the setting is suitable for their habitability, mainly regarding accessibility and reduction of exposure to threats.

Only four companies obtained high-level products with a score of "4" because they have industrialization and digitalization capacity and use BIM technology to plan individual solutions such as housing complexes. It is very likely that, through adaptations, some of the companies that scored level "3" can contribute to establishing articulations, requirements, and inspections of processes and products since, according to the evaluation carried out, it is seen that these actions are necessary.

Figure 1 presents the distribution percentage of companies by region and the types of companies, formality, and complexity observed.

69% of the companies are located in the Metropolitan Region, 20% in Valparaíso, and 11% in Libertador Bernardo O'Higgins. Construction companies predominate, with 83% of the studied sample. As for formality, 83% of companies are formal, and 17% are informal (this condition was verified for companies evaluated in the SII registry). On the other hand, the most frequent level of complexity is low, at 54%. 35% of them are at a medium level, and only 11% of these companies are of high complexity. This is according to information from the products' sales and the search in official sources such as the State's public market and tenders.

Table 5 describes the aspects considered to establish the sales prices of prefabricated houses. The Likert scale was assigned according to attributes delivered after online quotes, which was carried out to know details of how they usually break down the values, starting from a basic kit, including insulation as a compliment, extra costs for transportation, installation with or without sanitary connections up to complete turnkey service. This information considers the marketing used and added value for each order. This was used to check that companies are explicitly considering compliance with current regulations regarding, for example, thermal insulation of houses, a

Table 5. Aspects considered in the add-ons of prefabricated houses based on additional technical criteria and/or services. Source: Preparation by the authors.

Description of the level assigned	Level.
Minimum characterization of the product: materiality, surface area, price, and only offers KIT to assemble. Offers freight with an additional cost per km traveled	1
Suitable characterization of the product. Adds blueprints and constructive details of the KIT. There is clarity of what is included and what is not; offers freight with additional cost for transfer of the kit or turnkey houses but does not indicate thermal insulation	2
Offers all of the above and a service with separate installation charges or outsources the installation (workers to contact), freeing itself from responsibilities. Offers thermal insulation on request	3
Offers all of the above, possesses and demonstrates experience and clarity of an installed product. Includes thermal insulation	4
It offers all of the above, and it is the most reliable option, although its price is higher. It can be verified that it is a housing solution that meets the OGUC criteria, including thermal insulation and more sustainable building codes (CCS)	5

mandatory technical criterion according to the OGUC since 2007 for all new dwellings. The results show that most companies in the sample offer this and other services with separate charges in addition to the basic kit, which is quoted independently, so buyers can choose not to include it.

The purpose of this study was to apply a simpler version of indicators than the IISS previously published by Garay *et al*. (2022) after reflecting on the vulnerability and lack of sustainability of living by not taking into account territorial conditions, installing housing in areas of risk, exposure to earthquakes, volcanoes, and forest fires, among other threats, without understanding their importance. This research aims to draw attention to the supply of prefabricated wooden houses for three regions of central Chile: Valparaíso, Metropolitan, and O'Higgins. The results could be extrapolated to most of Latin America. Therefore, it is appropriate to look closer at the opportunity this productive sector has to manage processes that demonstrate sustainability, preparedness, and preventive actions associated with the new way of life that climate change is causing.

Overall, it was found that most companies use wooden elements of varying sizes. However, they do not comply with treated wood use per NCh 819 (INN, 2019), included in the OGUC. This was confirmed after visually checking the products and realizing there was no evidence of wood treated with preservatives or modified woods. There are also marked differences in the companies analyzed regarding technological capacity and incorporation of digitization using BIM, aspects that were not examined further. However, it was seen through the types of products and solutions that only a few explicitly state the use of technologies, digitization, computer design, or similar options. According to the figures in Table 3, 23 companies in the Metropolitan region, 8 in Valparaíso, and 4 in O'Higgins, were rated at level 3 of the Likert scale. This implies that they can potentially manufacture and supply houses with some additional requirements.

The Ministry of Housing and Urban Planning's Technical Division (DITEC, in Spanish) has announced the legal framework to regulate the industrialization companies it will use to reduce the housing deficit (BCN, 2023a). Four companies from the wood construction sector have been authorized, with projects for social housing and medium-rise buildings. These have made progress in regulatory compliance, using technology and BIM in production processes, coordinating industrialization in the factory, and making it possible to link up with other suppliers. In this way, Chile's wooden housing market could grow and develop even as an export product for Latin America.

As part of comprehensive solutions, the interaction between energy, seismic design, and other relevant technical criteria, such as fire resistance, is expected. Thus, it is vital to remember that this research shows that compliance with technical regulations is not being monitored when these houses are purchased on the private market. Martínez Gamboa (2022) found a similar result in his evaluation regarding the thermal subsidies of the Family Heritage Protection program and their effects on overcoming energy poverty in Chile and pointed out that "the most vulnerable households have not been focused on. This results from deficient handling by the program's leaders and the allocation of thermal subsidies with non-conforming goals considering the resources delivered, which has been done indirectly, sectorized, and without suitable monitoring and supervision" (p. 2). He also states that this is added to the problems caused by decentralizing public institutions, the lack of characterization and targeting of beneficiaries with territorial relevance, and transversal energy poverty. (Martinez Gamboa, 2022)

Under the life cycle analysis logic, by building with wood and protecting it, fewer forests would need to be cut down to build and/or heat, there would be less need for transportation, the useful life would be extended, and the need to recycle, replenish, and reuse would decrease up to three or four times more if the wood is treated correctly.

Presenting and describing this industry aims to highlight the existing productive capacity, make the adjustments to comply with the rules, strengthen the users, and do whatever is necessary to make this productive sector a more integrated, prosperous, and beneficial player for society.

So far, international research has been limited to identifying the actual behavior, construction technology, and design factors influencing thermal comfort and fuel consumption in dwellings. Location aspects, accessibility, and other factors that affect access to housing have been left aside, even though there is an increasing asynchrony between the needs and rhythms of the State (Penalty *et al.*, 2022; Mendia, 2022; Felmer, 2018).

Finally, it is worrisome that safety in the region, regarding exposure to threats, has yet to be included in the regulations. Even though changes are perceived, actions are lacking, such as showing the advantages from a life cycle analysis regarding the final destination of construction materials, where wood tends to be better. However, this must be highlighted as an attribute in the still unsophisticated market of prefabricated houses. Thus, the three Reduce - Reuse- Recycle (R–R–R) elements must also be promoted.

CONCLUSION

This industry is characterized by providing housing with kit-to-assemble, assembled, and, to a lesser extent, turnkey modalities. It is circumscribed mainly to construction factories, 83% of them, more than to real estate ones. However, both participate in the supply of housing solutions and, therefore, should be regulated by the State through actions to empower the productive sector, especially remanufacturing, which is currently focused on offering products and has not managed to become part of a larger ecosystem that impacts sustainable construction, since it has industrialization capacities.

The largest group of companies among those studied is located in the Metropolitan Region, with 69%, followed by the Valparaíso region with 20%, and finally, the O'Higgins region with 11%. As for formality, 83% are formal companies, and 17% are informal.

54% have low complexity, 35% medium complexity, and 11% high complexity, which shows the companies' level of preparation to face markets with higher demands for compliance with technical criteria, deadlines, and costs.

The overall evaluation of the 88 companies showed that 2.7% obtained level 1, 37.5% obtained level 2, 58.6% level 3, and only 1.1% were placed in level 4; none obtained level 5.

This information is relevant to fostering interest in these companies and providing more technical information to customers regarding their products, especially concerning current regulatory compliance. In addition to highlighting environmental aspects, some may exist and are not highlighted. In other cases, adjustments should be made to satisfy the demand according to requirements that are increasing annually.

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RECOGNIZING LIGHT AND THERMAL BEHAVIOR IN THE STRUCTURE AND FUNCTIONALITY OF BABER-ROOMS IN THE VERNACULAR BUILDINGS OF BANDAR LENGEH

RECONOCIMIENTO DE LUZ Y COMPORTAMIENTO TÉRMICO EN LA ESTRUCTURA Y FUNCIÓN DEL CAZADOR DE VIENTO BABER EN LA ARQUITECTURA VERNÁCULA DE BANDAR LENGUÉ

RECONHECIMENTO DO COMPORTAMENTO LUMINOSO E TÉRMICO NA ESTRUTURA E NA FUNCIONALIDADE DAS BABER-ROOMS NOS EDIFÍCIOS VERNACULARES DE BANDAR LENGEH

Hamed Mohammadi-Mazraeh
Master
PhD Candidate of Architecture, Department of Architecture, Aras international Campus
University of Tehran, Aras, Irán
https://orcid.org/0000-0003-0861-7614
hmm.mohammadi@gmail.com (Correspondence Author)

Mohammadreza Mahmoudzadeh
Master of Architecture
Department of Architecture, Bandar Abbas Branch
Islamic Azad University, Bandar Abbas, Irán
https://orcid.org/0009-0001-5872-3688
mhr.mahmoodzadeh@gmail.com

RESUMEN

La ciudad portuaria de Bandar Lengué se ubica en una región con un clima cálido y húmedo, en el sur de Irán. Como resultado, y dada la inclemencia del clima, se han desarrollado múltiples elementos y espacios para crear un tipo especial de arquitectura sostenible: un cazador de viento Baber. Ya que no hay evidencia de ningún estudio científico relacionado con esta infraestructura, o con su análisis, esta investigación se ha realizado en dos partes, estructural y funcional, para entenderlas mejor como una estructura estable. Para este examen se escogió el área de Bandar-Lengué (36 casas con 70 años de antigüedad o más) para un estudio cualitativo (presentando al cazador de viento Baber, sus componentes, materiales y proceso de construcción, las áreas ocupadas, la orientación y su posición) y cuantitativo (medición de luz usando el software de análisis Ecotec y mediciones de temperatura con un dispositivo "Fluke T3000c"). Esto se realizó en un momento en el que el aire acondicionado mecánico no era el estándar, para ver si estas habitaciones podían satisfacer las necesidades de los habitantes como un aire acondicionado natural.

Palabras clave
ligera, comportamiento térmico, cazador de viento Baber, clima, Bandar Lengué.

ABSTRACT

Bandar-Lengeh is located in a region with a hot and humid climate in the south of Iran. As a result, given its harsh weather conditions, several elements and spaces have been devised to create a special kind of sustainable architecture, a Baber-Room. Since there is no evidence of any scientific study regarding Baber-Rooms or their analysis, this research has been conducted in two parts, structural and functional, to better understand them as a stable structure. To examine these, an area of Bandar-Lengeh was chosen (36 houses aged 70 or above) for a qualitative (introducing the Baber-Room, its components, materials, and construction process, the occupied areas, orientation, and positioning) and a quantitative study (light-measurement using Ecotect analysis software and temperature measurements with a "Fluke T3000fc" device). This was done at a time when mechanical air-conditioners were not standard, to see whether these rooms could meet the needs of inhabitants as natural air-conditioners.

Keywords
light, thermal behavior, Baber-room, climate, Bandar Lengeh.

RESUMO

Bandar-Lengeh está localizada em uma região de clima quente e úmido no sul do Irã. Como resultado, dadas as condições climáticas adversas, vários elementos e espaços foram planejados para criar um tipo especial de arquitetura sustentável, uma Baber-Room. Como não há evidências de nenhum estudo científico sobre as Baber-Rooms ou sua análise, esta pesquisa foi conduzida em duas partes, estrutural e funcional, para melhor compreendê-las como uma estrutura estável. Para examiná-las, foi escolhida uma área de Bandar-Lengeh (36 casas com idade igual ou superior a 70 anos) para um estudo qualitativo (apresentando a Baber-Room, seus componentes, materiais e processo de construção, as áreas ocupadas, a orientação e o posicionamento) e um estudo quantitativo (medição de luz usando o software de análise Ecotect e medições de temperatura com um dispositivo "Fluke T3000fc"). Isso foi feito em uma época em que os condicionadores de ar mecânicos não eram padrão, para verificar se essas salas poderiam atender às necessidades dos habitantes como condicionadores de ar naturais.

Palavras-chave:
luz, comportamento térmico, Baber-Room, clima, Bandar Lengeh.

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INTRODUCTION

Sustainable architecture can be defined as any experience contributing to what humans use for a more suitable environment (Jaradat, Alshboul, et al. 2024). This is increasingly relevant within a context where the construction industry has been responsible for approximately 30-40% of global energy use, and energy-saving issues and applicability have become extremely important regarding the scale of buildings and architecture (Li, Zhai et al., 2024). In the past, the lack of mechanical cooling systems led to natural air-conditioning structures being used to provide comfort for users (Toroxel & Silva 2024) and in Iran, local architecture has attempted to provide greater comfort through elements (like wind towers and latticework) and stable spaces such as the Baber-Room to make their environment satisfactory (Mazraeh & Pazhouhanfar, 2018). These local buildings are taken into consideration as the source of continuous knowledge and the result of centuries of experience and contemplation (Baheretibeb & Whitehead, 2024), and as time has gone by, there has been an increasing familiarity with their role and practicality (Dwijendra & Adhika 2022; Sargazi, 2023). However, this type of architecture has undergone many changes over time.

Since ancient times, climate has played a very significant role in the advent of architecture as it is, but this is also true in architectural elements that are supposed to be a vital part in the recognition of compatible architecture with the climate of a particular region. However, it is the so-called tool, "people's awareness of climate," that has led to a stable development in architecture. In addition, local materials, elements, and spaces have provided users with comfort (Mazraeh & Pazhouhanfar, 2018). One of these elements is the use of latticework when it comes to windows. A variety of changes, simple windows, and latticework windows (Figure 4) in great numbers, especially in a Baber-Room, have been used to face unpleasant weather conditions, namely the high-light-intensity, heat, and moisture, without any mechanical cooling system (Mazraeh & Pazhouhanfar, 2020).

Despite all the evolutionary actions and novelty in the construction world, many Iranians still live in local houses, and surprisingly favor them (Foruzanmehr, 2015; Mazraeh & Pazhouhanfar, 2018). Inhabitants have been looking for methods and elements to provide thermal comfort in spaces (Sargazi, 2023), and to deal with/respond to the nature of climate (Razavian Alemi, et al., 2023).

Bandar Lengeh is one of the Iran's southern regions, characterized by a hot and humid climate. It features a unique space known as the "Baber Room," along with several vernacular architecture elements, which play a functional role in developing the region's native architecture. Since no prior studies or investigations have been conducted, this research adopts an innovative approach to understanding and validating the Baber Room's functional role in sustainability. The research seeks to answer the question of whether the Baber Room and its vernacular architectural elements have positively responded to sustainability issues when no mechanical ventilation systems were available.

METHODOLOGY

The architecture of a Baber-Room in Bandar-Lengeh follows a unique style seen in the region, especially in harsh weather situations. After the wind towers found on roofs, it is the oldest and most applicable natural air conditioner. Because no study was found to examine/introduce the Baber-Room's natural air-conditioning system, the decision was made to analyze an old context, including 36 houses aged 70 or above. Using a qualitative (introducing the Baber-Room, its components, materials, and construction process, the occupied areas, orientation, and positioning) and a quantitative study (light and temperature measurements using software and a device, respectively), it was determined to scrutinize the functional and structural features of this space. For the structural aspect, the materials, construction process, and components (latticework, shading, the amount of surface usage in three Baber-Room styles) were examined, while the functional part deals with the light analysis and studies the room in two different modes. To do this, the room temperature was measured throughout 24 hours of the day on the 17th of each month.

CASE STUDY

Bandar-Lengeh, with its 8,210 km^2, is located southwest of the Persian Gulf coast (Figure 1). On being next to the sea, it is exposed to a hot and dry coastal air mass plus mild and humid sea air. Consequently, sometimes 60 km/h winds are recorded, blowing from the sea toward the coast. According to the measurements shown in Table 1, the temperature ranges from 33° to 45° C. The hottest period is called "Khoradad" and "Shahrivar," which is unpleasant for users. Moreover, high humidity of up to 100% can often be observed because of the proximity to the sea. Although hotness and humidity produce a challenging and harsh situation, the local architecture of Bandar-Lengeh, thanks to the devised spaces and elements, can subtly handle the situation of its inhabitants (Mohammadi Mazraeh, 2022). It also has facilitated and comforted people's lives in internal spaces (Mohammadi Mazraeh, 2021), in a way that Arabs living around the Persian Gulf come to walk in this region (Mazraeh & Pazhouhanfar, 2018).

ARCHITECTURAL FEATURES OF BANDAR-LENGEH

The first sample of a Baber-Room appeared among houses that are over 70 years old (Figure 2A), where all the houses had a Baber-Room on the roof. Over time,

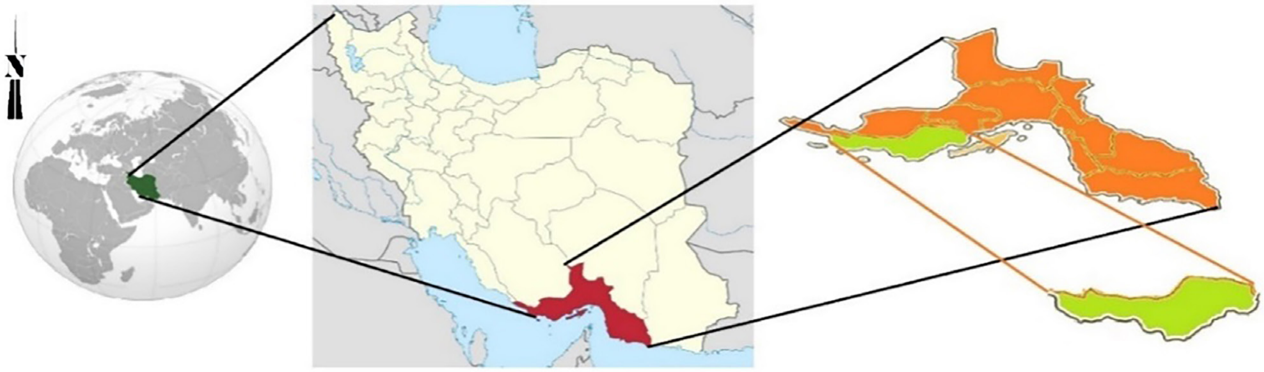

Figure 1. Bandar-Lengeh on a map of Iran and in the world. Source: authors' elaboration

Table 1. Values (PET) for different months in Bandar-Lengeh (Roshan, Yousefi et al., 2018)

Jan	Feb	Mar	Apr	May	Jun
Comfortable	Comfortable	Slightly warm	Warm	Hot	Very hot
19.5	21.3	24.9	31.2	37.6	41.4
Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Very hot	Very hot	Hot	Warm	Slightly warm	Comfortable
43.2	43.1	40.1	34.7	27.3	21.8

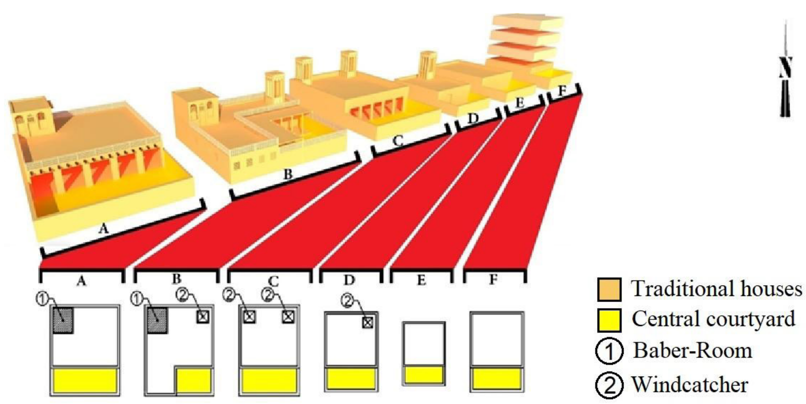

Figure 2. A variety of construction methods from 70 years ago up until the present day. Source: authors' elaboration

among the buildings aged from 50 to 70 years, it can be noticed that Baber-Room is built sometimes with a wind tower or alone on the roofs (Figure 2A & Figure 2B). However, in buildings between 30 and 50 years old, there is only a single or a pair of wind tower(s) (Figure 2C & Figure 2D). In more recent buildings (less than two decades old), the only thing that can be observed is the existence of natural air-conditioning through latticework and or simple windows (Figure 2E). Finally, in the last two decades, with the advent of apartments (Figure 2F) besides the traditional context, a sense of dissatisfaction has spread among the users of A, B, C & D towards the loss of privacy in yards, the lack of safety in earthquakes, and the possibility of badly-made new buildings collapsing on traditional houses.

RESULTS

STRUCTURAL ANALYSIS AND COMPONENTS

An introduction to the Baber-room

In traditional societies, families required places that could facilitate activities such as sitting, eating, sleeping, gathering as a family, entertainment, and for privacy (Mohammadi Mazraeh, 2022). This can be perceived in the role of the Baber Room.

Baber-Rooms can be square or rectangular shaped and are normally 4*4, 6*4, and 6*6 in size. They are located

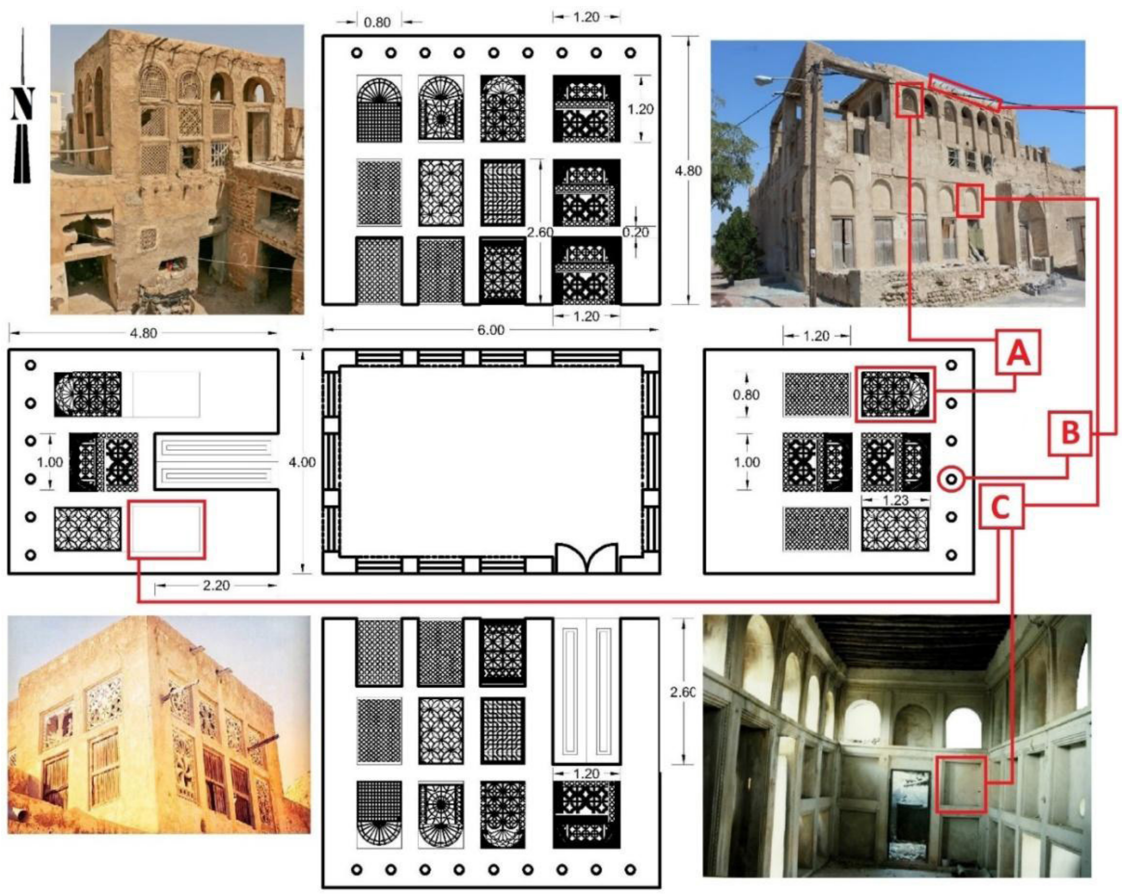

Figure 3. The Baber-Room layout, including its elements. Source: authors' elaboration

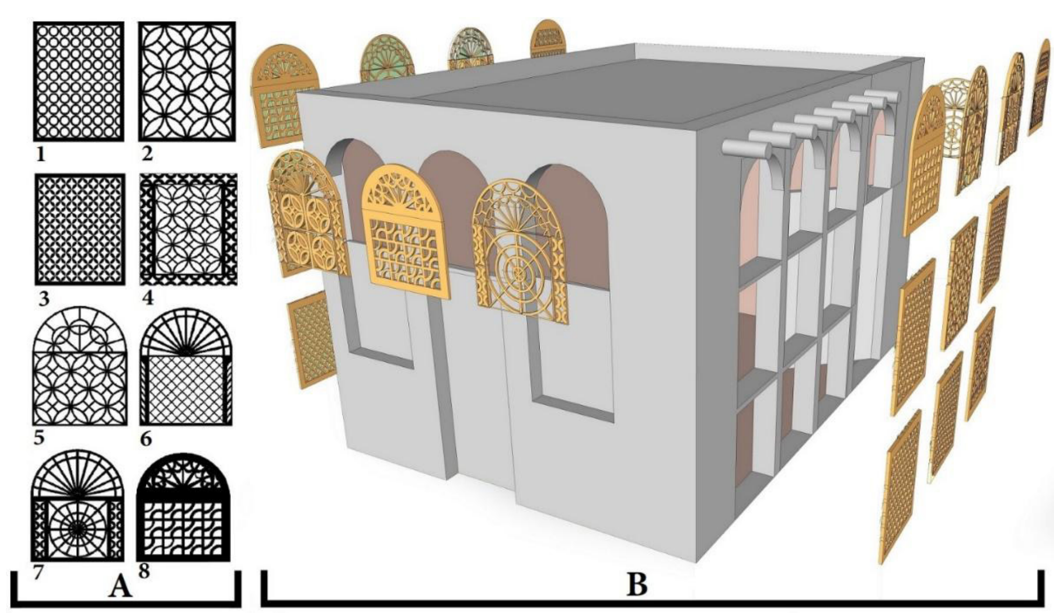

Figure 4. Three-dimensional view of the Baber-Room's internal space. Source: authors' elaboration

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Table 2. The amount of empty and used area for the eight most commonly used latticeworks. Source: authors' elaboration

Row	Model type	Used surface area	Empty surface area	Total area (cm)
1	1	39%	61%	960(100%)
2	2	32%	68%	960(100%)
3	3	38%	62%	960(100%)
4	4	34%	66%	960(100%)
5	5	32%	68%	960(100%)
6	6	39%	61%	960(100%)
7	7	32%	68%	960(100%)
8	8	43%	57%	960(100%)

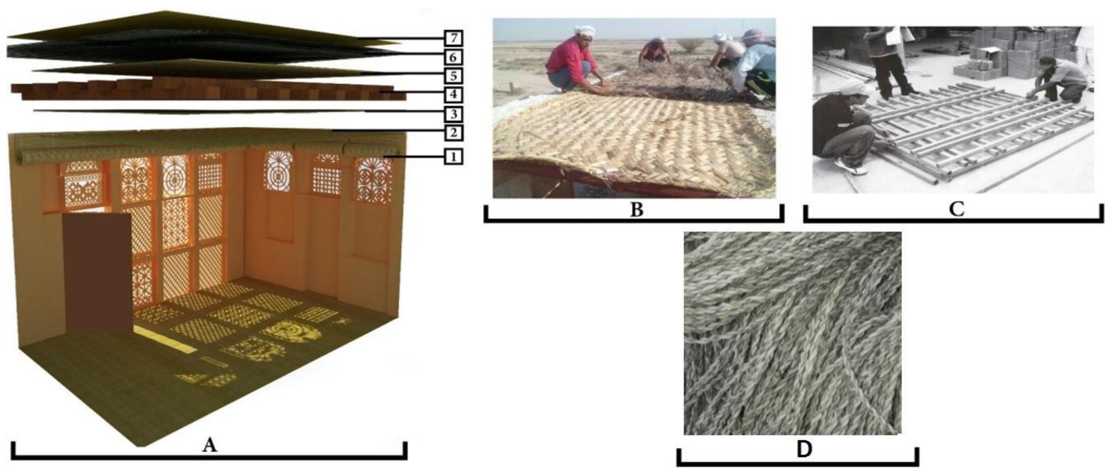

Figure 5. Architectural structure of the Baber-Room's roof. Source: authors' elaboration

on the top floor and are accessible through stairs built at the entrance to the house, or ones in the living room or family room, to the roof/internal space of the Baber-Room (Mazraeh & Pazhouhanfar, 2018; Mazraeh & Pazhouhanfar, 2020). This room is a perfect instance of the sustainable architecture of Bandar-Lengeh (Figure 3), given its variety of components such as latticed windows (Figure 3A), squared timber (Figure 3B), and niches (Figure 3C). Its walls provide suitable conditions for users to sleep, eat, read, etc., by receiving wind from the sea and absorbing light from early afternoon to late morning.

Latticework

Muslims' houses follow a unique design that has even been emphasized in Islam (Putri & Sunesti, 2021), where privacy in traditional architecture has had a noticeable impact on user satisfaction (Philokyprou & Michael, 2021). Their latticework has commonly been devised as thick curtains ever since the Safavieh Dynasty in Iran. With the latticework, the interior space would not be visible all day long for privacy (Babaei, Soltanzadeh et al., 2013). It also prevents light from entering the house to some extent (Mohammadi Mazraeh, 2023), and the inhabitants can comfortably do their everyday chores. In the past, local architects and users tried to place latticework facing most regional winds (often towards the sea) to experience better air conditions inside the building by directing the wind. Such buildings are often seen in Bandar-Lengeh. The bottom line is that all these functions are there only for user comfort (Nemat Gorgani, 2002; Mazraeh & Pazhouhanfar, 2018). Figure 4 shows the eight most common latticework models in Bandar-Lengeh. Meanwhile, Table 2 shows the proportion of empty compared with non-empty areas, which ranges from 57% to 68%. This is to bring beauty and light into the interior space for user satisfaction.

Materials and construction process

Local architecture has demonstrated its positive attitude towards nature and cultural significance in black and white (Chen, Xie et al., 2020), while using local components and materials has been an effective action for the design (Mazraeh & Pazhouhanfar, 2018). It has considered that intense heat, moisture, and light to an extreme degree in Bander-Lengeh requires taking advantage of a specific architecture that provides users with comfort, where possible. One of the solutions is to be familiar with climate change to be able to deal with bad weather conditions. Indicators such as taking advantage of local materials

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(thatch, mortar, stone, plaster), recognizing spaces and utilizing them in the opposite direction of sunlight, wall thickness (to protect the building against heat/moisture), using plenty of latticework in the room's wall, positioning a Baber-Room at high altitude and using high-ceilings, play a notable role in this. The main materials used for the ceilings according to Figure 5 are (from indoor to outdoor): 1-mat (light-absorbent type) (Figure 5B) 2-rope fabricated out of date tree leaves (Figure 5D) 3-covering mat 4-squared timber vertically and horizontally on each other (Figure 5C) 5-covering mat 6-date tree leaves 7- thatch. Every single component truly expresses the connection and interrelation between architecture and nature for the special role of Baber-Rooms such as light-absorbent mats to prevent intense light from penetrating the place, rope to hang the mat on the roof, covering mat made from leaves of a date tree, and also this same material for scattering and thickening against heat to avoid dust descending from the ceiling inside the house, squared timber to hold and bear the weight of the ceiling, and thatch to cover the walls and ceiling to provide cooling and heating in summer and winter, respectively.

SHADING, WINDOWS AND ORIENTATION

Shading and windows (A place to be away from sunlight)

Shading (Figure 6) was one of the very few options used to prevent intense light and hot wind (on the east/west side of the Baber Room) from entering. This was created as a porch to expand latticework on the rooms' walls, besides adding space with shading so users could take advantage of it throughout the day. Among the 36 Baber-Room cases in Bandar-Lengeh, only two included a room with shading.

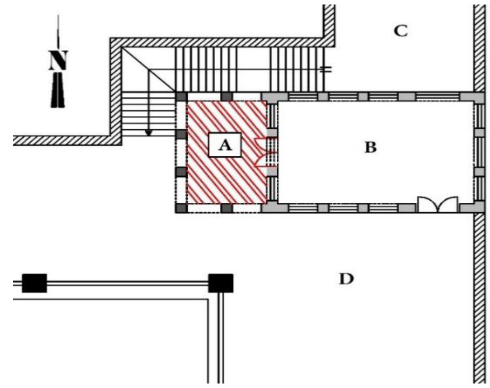


Figure 6. Space occupied by shade on the floor (part A) and in view (part B). Source: authors' elaboration

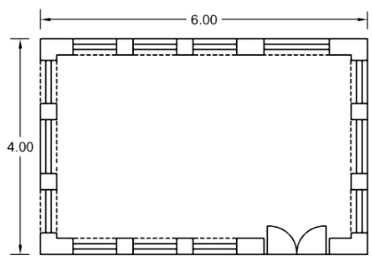
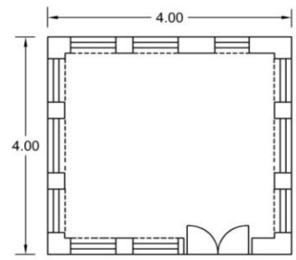
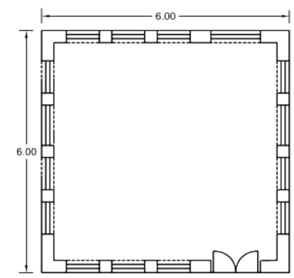
The proportion of areas used in the Baber-Room in three styles

The Baber-Room included areas such as a wall, a niche in the wall (Figure 3C), the door area, and the lattice window (Figure 3A) that occupied a specific area of wall which is determined through the measurements and data in Table 3. At a glance, it can be concluded that the maximum average of the areas is (in order): wall with 13.25 m^2, lattice window with 6.62 m^2, niche with 4.5 m^2, and door with 1.23 m^2. As it can be perceived, they tried to use lattice windows as much as possible in north and south, with 8.93m^2 and 10.42m^2 (in order), to provide daylight and natural air-conditioning inside the room.

Table 3. Rate of use of each area on different sides. Source: authors' elaboration

Room expanse (m)	Entire wall area				Wall area (m^2)				Niche area on the wall (m^2)			
	N	S	W	E	N	S	W	E	N	S	W	E
4*4	19.2	19.2	19.2	19.2	9.9	8.38	11.5	11.5	0	0	7.7	7.7
4*6	28.8	28.8	19.2	19.2	15.84	15.6	11.6	12.96	0	0	2.24	0
6*8	38.4	38.4	28.8	28.8	17.4	16.28	13.28	14.8	12	10	6.4	8
Component average	28.8	28.8	22.4	22.4	14.38	13.42	12.13	13.09	4	3.33	5.45	5.23
Average						13.25				4.5		
Room expanse (m)	Latticed window (m^2)				Door's surface				Ratio of the total wall area to the niche			
	N	S	N	N	N	S	W	E	N	S	W	E
4*4	9.3	7.7	0	0	0	3.12	0	0	2.06	2.49	2.49	2.49
4*6	12.96	10.08	3.12	6.24	0	3.12	3.12	0	2.22	2.86	3.58	3.08
6*8	9	9	6	6	0	3.12	2.24	0	1.83	2.02	2.32	2.06
Component average	10.42	8.93	3.04	4.08	0	3.12	1.79	0	2.04	2.46	2.80	2.45
Average		6.62				1.23						

Table 4. Orientation of Baber-Rooms. Source: authors' elaboration

Type of room						
Model	A		B		C	
						
	Quantity	Percentage	Quantity	Percentage	Quantity	Percentage
	28	77.8%	5	13.9%	3	8.3%

ORIENTATION

When designing and building the Baber Room to address climate awareness, spaces were structured considering local weather conditions. These elements include locating the largest rooms from east/west considering their use and length (Mazraeh & Pazhouhanfar, 2018). According to Table 4, among the 36 buildings with Baber-Rooms, it was seen that there were 28 south/north rooms of 6*4, five rooms of 4*4, three rooms of 6*6 (m^2) and only two east/west rooms were found. In model C, two are shown on the east/west side.

TEMPERATURE MEASUREMENTS

The Fluke T3000fc thermometer (Figure 7), used inside the Baber Room to measure temperature, can be used to determine thermal conditions under challenging circumstances like those of Bandar-Lengeh. Fluke Connect allows users to record measurements online by connecting applications and sharing the temperature via the "share live" option. Another advantage of this device is that it can measure temperatures ranging from -200° C to +1,372° C, at a 0.1° C resolution, with an operating temperature from -10° to +50° C, entry protection (IP42), and ITS-90 (thermal-scale). This device is used inside the Baber Room to measure temperature.

Physiological equivalent temperature, or PET, is a well-known indicator used to measure and compare different degrees of heat and physiological stress on humans. It is used here to measure the temperature of Bandar-Lengeh and the interior space of the dwellings (Table 5).

In the past, the temperature was presumed to be one of the substantial indicators of comfort in a building. The Baber-Room could be compatible with different regional climate situations because of its local architectural elements and it provides satisfaction for users. To determine the temperature accurately on the 17th day of each month (for 24 hours), the "Fluke T3000fc" thermometer was placed inside the Baber-Rooms at the height of 1.2 meters (Sleeping space pattern in Table 7) from the floor to examine whether a Baber–Room with 63.4% of use per day (compared to other spaces) can provide better

Figure 7. "Fluke T3000fc" device for measuring temperatures. Source: Authors' image

Table 5. Physiological equivalent temperature – PET (Matzarakis, Mayer et al., 1999).

PET (°C)	Thermal sensation	Physiological stress level
<4	Very cold	Extreme cold stress
4–8	Cold	Strong cold stress
8–13	Cool	Moderate cold stress
13–18	Slightly cool	Slight cold stress
18–23	Comfortable	No thermal stress
23–29	Slightly warm	Slight heat stress
29–35	Warm	Moderate heat stress
35–41	Hot	Strong heat stress
>41	Very hot	Extreme heat stress

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Table 6. Internal temperature of the room at different times of the day during a year. Source: authors' elaboration

DATA	January		February		March		April		May		June	
HOUR	Outside	Inside	Outside	Inside	Outside	Inside	Outside	Inside	Outside	Inside	Outside	Inside
0	19.5	21.7	20.3	22.2	20.8	23.2	22.3	24.7	35.7	29.8	33.7	31.2
1	19.3	21.3	20.2	22	20.5	23.2	21.6	24.6	34.5	28.5	33.2	30.6
2	19.1	21.1	20	21.8	20.1	23	20.8	24.3	33.1	28.8	32.6	30
3	18.8	21	19.8	21.5	19.7	22.8	20	24	31.8	28.4	32.1	29.7
4	18.7	21.4	19.7	21.5	19.2	22.7	19.3	23.9	30.5	28.1	31.6	29.1
5	18.5	21.1	19.6	21.4	18.8	22.6	19.3	23.9	30.8	28.4	32.2	30
6	18.3	21.3	19.8	21.5	19.8	23.2	20.6	24.9	32.1	29.8	33.2	31
7	19.3	21.7	19.8	21.5	21	24.1	22.2	25.7	33.7	31.2	34.6	31.4
8	19.3	21.9	20.3	22.8	22.2	25.2	23.5	27.2	35.2	32.9	35.9	31.9
9	19.5	22.1	21.7	24.3	23.5	26.2	25.1	27.1	36	33.7	37.2	35.2
10	21.3	24.5	22.6	24.9	24.8	26.8	26.6	27.8	36.7	37.3	38.2	35.4
11	22.6	25.3	23.6	25.7	25.5	28	27.8	28	37.1	39	39.1	36.3
12	23.2	25.3	24.3	26.1	26.1	28.6	28.6	28.6	37.3	39.1	39.7	36.7
13	23.6	25.4	24.8	26.5	26.3	28.8	29	28.2	39.5	39.2	40.1	37.1
14	23.8	25.9	25.2	26.8	26.3	29	29.2	27.7	38	38.4	40.1	37.3
15	23.2	25.4	25.1	26.7	26.2	28.8	28.8	27	37.6	37.1	39.7	37
16	22.5	22.4	24.6	25.8	25.5	28.3	28.1	26.6	37	36.3	39.2	36.7
17	22.3	21.8	24	25.4	24.5	26.2	27	25.7	36.1	34.7	38.4	35.4
18	22.2	21.8	23.6	21.8	24.2	23.5	26.3	25	35.4	33.4	37.4	35.1
19	22	21.7	23.3	21.8	23.8	23.5	25.8	25	34.7	31.6	36.7	34.4
20	21.8	21.1	22.8	22.4	23.3	23.6	25.3	25.1	34	30.7	36	33.7
21	21.6	21	22.6	22	23.1	23.7	24.8	25	33.2	30.1	35.2	33.1
22	21.5	21.1	22.2	22.1	22.7	23.6	24.2	24.9	32.5	29.7	34.6	32.4
23	21.3	21	21.8	21.4	22.3	23.5	23.7	24.9	31.8	29.1	33.9	32
Average	20.97	22.43	22.15	23.33	22.93	25.09	24.58	25.83	34.76	32.72	36.03	33.45
DATA	July		August		September		October		November		December	
HOUR	Outside	Inside	Outside	Inside	Outside	Inside	Outside	Inside	Outside	Inside	Outside	Inside
0	35.7	33.4	33.9	32.5	30.8	28.4	27.8	25.3	24.5	23.7	20.1	20.4
1	36.2	34.3	33.2	31.8	30.6	28.1	27.5	25.1	23.8	22.8	19.2	19.6
2	36.6	34.8	32.7	31.1	30.3	27.6	27.1	24.5	23.2	22.6	18.3	18.8
3	36.9	34.9	32.2	35.4	30	28.9	26.6	24	22.5	21.8	17.5	17.7
4	37.2	35.5	31.8	30.8	29.8	27.2	26.2	23.8	21.8	20.6	16.6	16.9
5	37.6	35.9	31.8	30.3	29.5	27.4	25.8	23.1	21.2	20.4	15.6	16
6	38.2	36.7	32.4	30.7	30.3	27.9	26.8	24.9	21.6	20.6	14.9	15.3
7	39.1	38.1	33.1	30.9	31.1	29.3	28.1	26.6	22.7	21.9	17.1	17
8	40	38.7	34.2	31.9	32.2	30.8	29.3	27	24.1	23.2	19	18.8
9	40.9	40.1	35.4	32.4	33.2	31.6	30.6	27.2	25.3	24.1	20.3	20.5
10	41.7	40.3	36.2	32.8	34.2	32.4	31.6	27.9	26.3	25.8	21.5	21.8
11	42.7	40.4	36.9	33.4	34.7	32.7	32.4	28.7	27.1	25.3	22.2	22.6
12	43.2	40.8	37.5	33.8	35.2	33.6	32.7	28.9	27.5	25.2	22.7	23
13	43.7	40.3	37.9	34.2	35.4	33.7	33.1	29.5	27.7	25.3	23	23.9
14	43.9	41.1	38.1	34.4	35.2	33.7	32.9	28.6	27.3	25.8	22.5	23.4
15	43.7	40	38	34.1	35	33.4	32.5	28.8	26.7	25.3	21.8	22.4
16	43.5	39.6	37.5	33.9	34.4	32.9	31.6	28.2	25.8	24.2	20.5	22.7

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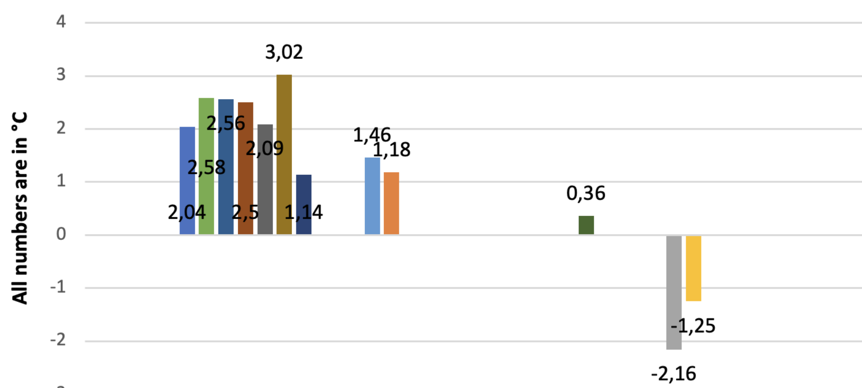
17	42.9	38.2	36.7	33.3	33.7	32	31.1	27.8	25.5	24.7	20.2	20.4
18	42.2	37.5	36.2	32.6	33.2	30.7	30.6	27.2	25.2	24.3	19.8	19.6
19	41.7	37.4	35.7	32.2	32.9	30.3	30	26.9	24.8	24	19.6	19.3
20	41.1	37.4	35.1	31.6	32.6	30	29.5	26.4	24.6	23.4	19.3	19
21	40.6	37.4	34.6	32	32.2	29.6	29	25.8	24.2	23.1	19	19.4
22	40	37.1	34	31.6	31.8	29	28.5	25.3	23.8	22.7	18.7	19.1
23	39.4	37.2	33.5	30.8	31.1	28.6	28	25.1	23.6	22.6	18.3	18.9
Average	40.36	37.8	34.94	32.44	32.49	30.4	29.55	26.53	24.62	23.48	19.49	19.85



	Positive effect	Neutral	Negative effect
jan		1,46	
feb		1,18	
mar			-2,16
apr			-1,25
may	2,04		
jun	2,58		
jul	2,56		
aug	2,5		
sep	2,09		
oct	3,02		
nov	1,14		
dec		0,36	

Figure 8. Positive, negative, and neutral role of the Baber-Room compared to the outside-temperature. Source: authors' elaboration

comfort for users of traditional constructions.
According to the data in Table 5, Table 6, and Figure 8, it can be seen that the behavior of the Baber-Room in different months of the year is divergent. In January and February, when thermal-conditions are comfortable, a 1.46 and 1.18 (average temperature at different hours from Table 6) degree temperature increase, respectively, can be seen inside (noted as neutral). In March, the thermal condition is supposed to be slightly warm, and a 2.04-degree increase in temperature can be perceived inside (noted as an adverse effect). However, in April, similarly to March, a 1.25-degree increase in temperature leads to unpleasant conditions inside the Baber Room. People use these spaces less and less during the day/night in March and April.

However, the weather is hot in May and September, and temperatures that are 2.04 and 2.09 degrees lower, respectively, can be noticed. Meanwhile, in June, July, and August, when the weather is considered very hot, temperatures that are 2.5, 2.56, and 2.58 (respectively) degrees lower lead to a relaxing and suitable atmosphere in the inner space. In October, considered as warm, the temperature is 3.02 degrees lower, providing a safer and more pleasant environment for the users compared to outside. On the other hand, in November, which is slightly warm, the room has a temperature that is 1.14 degrees lower. On the other hand, December is comfortable in itself (noted as neutral), providing comfortable conditions for the Baber-Room users.

Mats are placed on the external walls of buildings to dissipate heat in areas with intense sunlight, as depicted in the left image of Figure 8. This practice helps to moderate the temperature entering the room, making it more pleasant. Additionally, these mats are sometimes dampened to create a cooler breeze within the room,

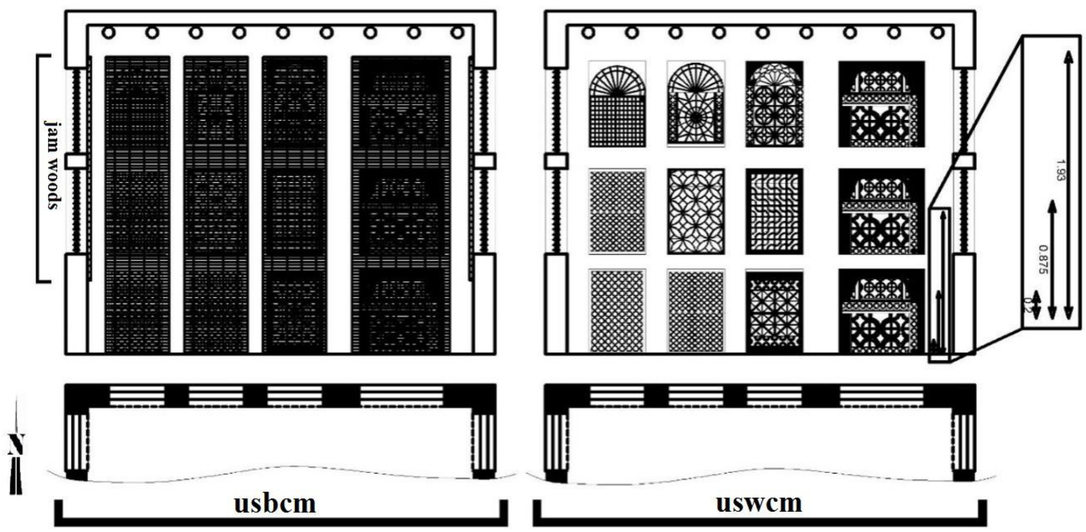
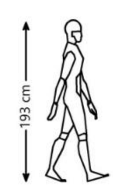


Figure 9. Light measurements in usbcm (left) and uswcm (right). Source: Authors' image.

Table 7. Different types of Baber-Room's usage (Neufert & Neufert, 2012).

	1	2	3
Position	Lying down (human body at 20 cm from the floor)	sitting (human body at 87.5 cm from the floor)	standing (human body at 193 cm from the floor)
			

enhancing the overall comfort level.

LIGHTING MEASUREMENTS

To analyze light in the environment and also the improvement of the building's energy efficiency, several software programs, including "Ecotect," are used. This software provides an advanced modeling method to analyze the role of light in the Baber-Room (Al-Saggaf, Nasir et al., 2020; Lisa, Zuraihan et al., 2021). According to several studies, it is concluded that modeling using Ecotect is very accurate and highly reliable (Salami, Abba et al., 2023; Xu and Liu, 2023). It is also suitable for designing and making initial calculations regarding photometric methods in the construction industry. Figure 9 is used to analyze the role of light in the Baber-Room under two different circumstances. One, with the use of mats, namely USBCM, and without USWCM, to see whether the Baber-Room could provide comfort at hot-peak-hours (i.e., 2 pm) for users in three different conditions or not.

Since people can take advantage of the environment by assuming different positions such as lying down, sitting, and standing, they need to have an interior space with the least light possible at the three heights. Table 7, considers conditions for the human body at 20 cm (lying down), 87.5 cm (sitting), and 193 cm (standing) from the floor, to assess the role of a Baber-Room with local architectural elements.

Considering that light is the second most important factor under observation after temperature in local construction, and according to results achieved in Table 8 and Table 9, it can be noticed that the worst period when extreme hotness is experienced is at 2 pm. In the three different positions examined in the Baber-Room (lying down, sitting, and standing) and in the two different setups (uswcm and usbcm), at 20 cm from the floor with the least light, 210 lux, in both uswcm and usbcm was the best place for users to relax. After that, the second best was at 87.5 cm from the floor with the least light, 240 lux, under the uswcm condition and at 210 lux, in usbcm. Finally, at 193 cm from the floor, the best option was with the least light, 280 lux, in uswcm, and 240 lux, in usbcm. The average

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Table 8. Light-intensity of the Baber-Room in both uswcm and usbcm. Source: authors' elaboration

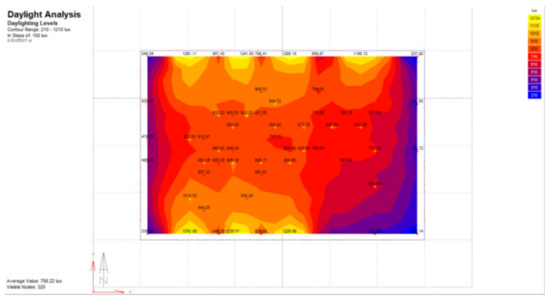
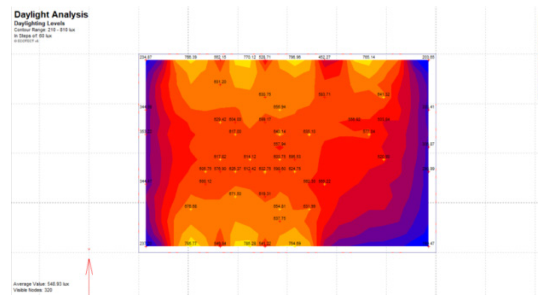
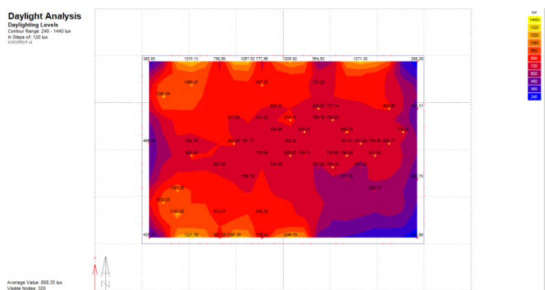
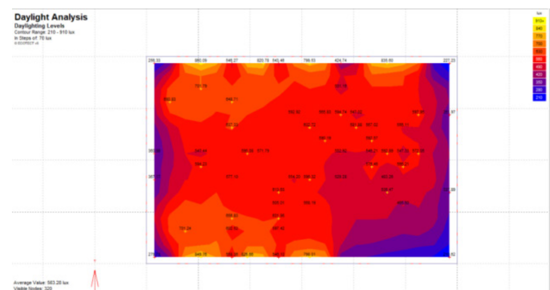
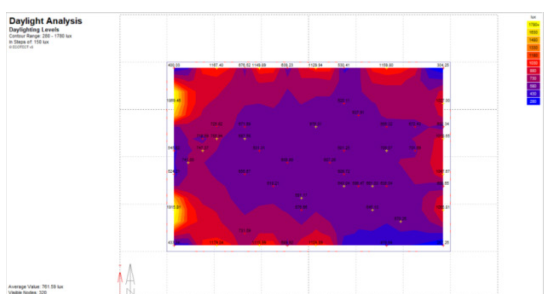
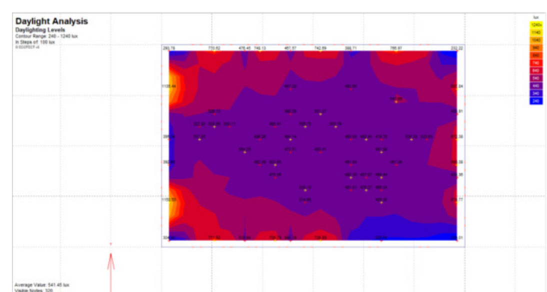
Position	Uswcm	usbcm
human body at 20 cm from the floor		
human body at 87.5 cm from the floor		
human body at 193 cm from the floor		

Table 9. Minimum and maximum light-intensity in uswcm and usbcm. Source: authors' elaboration

At a height of	Position			
	Without mat in LUX(uswcm)		With mat in LUX(usbcm)	
	Minimum	Maximum	Minimum	Maximum
20 cm from the floor	210	1210	210	820
87.5 cm from the floor	240	1440	210	910
193 cm from the floor	280	1780	240	1240
Average	243.33	1476.67	220	990

in all three, without the mat, is 243.3 lux. On the other hand, with the mat, at an average of 220 lux, there is a 23.33 lux reduction. Consequently, a more relaxed and pleasant light condition allows users to rest or sleep during the night compared to other situations without a mat.

The information on maximum light-intensity entering the space is collected as follows: at 20 cm from the floor with a maximum of 1210 lux in uswcm and 820 lux in usbcm (a 390 lux difference). At 87.5 cm it has a maximum of 1440 lux in uswcm and 910 lux in usbcm (a 530 lux difference), and finally, at 193 cm from the floor, there is a maximum of 1780 lux (the worst light entrance into the room) in uswcm, and 1240 lux in usbcm (a 540 lux difference).

Comparing the average in all three, without mat 1476.67 lux, and with mat 990 lux, a 486.67 lux reduction can be perceived, which led to increased user satisfaction for sleeping, resting, and relaxing.

According to similar existing research, the thermal performance used the Ecotect software as seen in the work of Sonawane and Vakhari (2023), who studied traditional Indian homes with a stone wall covering, clay, and slopped roofs made of straw. They discovered that the materials were environmentally friendly and provided comfortable temperature conditions for building occupants. In the study of Ratree et al. (2020), by examining the style of native houses in Bangladesh and Sri Lanka based on the region's climate, they looked at building techniques, passive design strategies, thermal comfort, etc. among mud houses in both countries using the Ecotect software, and recommended improvements to recover passive energy and increase user comfort in buildings. Ratree et al. (2020) also examined three styles of current European construction based on the collected information, showing that 74% of the participants are dissatisfied with this construction style. Unlike those building systems that were built with eco-friendly materials, they were very efficient, and the purpose of this was to analyze thermal comfort during a critical period of time. Meanwhile, Gupta et al. (2020) investigated the style of rural native buildings near Ranchi in the state of Jharkhand in eastern India, where Ecotect and Climate Consultant software were used, using houses made with materials from native resources, that have been able to create more suitable conditions for human life than new materials. In comparison to the current research, according to a review of the literature, it was found that no such research has been done on the Baber-Room style. This construction style demonstrates the attention of architects and users of local structures in the region (Hormozgan, Iran) to thermal comfort conditions and their knowledge of climate and materials. The building blocks of this research depict that this style has been able to create satisfaction among its users in the sense of thermal behaviors, light detection, and blocking excess light to make use of the wind currents.

CONCLUSION

Among the six different styles of building construction in Hormozgan-Iran throughout the last 70 years, the local architecture is important among building users and architects. One instance of such a building is located in the south of Iran and is known as the Baber-Room. Its unique construction style, which encompasses the methodical application of techniques, has caught the interest of everyone from tourists to building users and architects. Although the local architecture of Bandar-Lengeh has undergone many changes over time, it has kept its identity and introduced itself as valid evidence and documentation in the construction procedure. This local architecture uses specific elements (wind towers and latticework) along with spaces (Baber-Rooms) to provide comfort for users, particularly when no mechanical cooling system is used. The intention behind this article was to introduce the Baber-Room with structural analysis to scrutinize materials, the construction process, and its elements, such as latticework and local materials, shading, and the areas used in three different styles of Baber-Rooms, while assessing the Baber-Room under usbcm and uswcm conditions through functional analysis of light and temperature. In the photometric part, the person was evaluated in three positions (lying down, standing, and sitting) at 2 pm. Consequently, it is determined that the best conditions are uswcm and usbcm in lying down and sitting positions (20 cm and 87.5 cm from the floor) with 210 lux, while the worst condition is under uswcm when standing.

In comparison, measurements were taken standing (193cm from the floor) with a maximum of 1780 lux. On the other hand, using the temperature indicated, the most advantages are provided in May, June, July, August, September, and October, while January, February and December had a neutral temperature and minimal advantages. Finally, adverse conditions were seen in March and April resulting in the least use and benefit for the users.

Upon review, it has been determined that the Baber-Room exhibits specific strengths and weaknesses, as outlined in Table 10. Moreover, in the realm of research focusing on light analysis, the study by Ahmad, Prakash et al. (2022) investigated the influence of building materials on the entry of light and indoor temperature. This study revealed that

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Table 10. Strengths and Weaknesses of the Baber Room

	Strengths
1	The Baber-Room has been a favored space for a night's sleep, consistently attracting the attention of vernacular building users from the past to the present.
2	This area was primarily used for family gatherings during the late-night hours.
3	Using latticed window openings and positioning this space at the highest part of the building, occupants can maximize natural ventilation from the sea.
4	With its extensive geometrical design between latticed windows, the Baber-Room has successfully been used for natural ventilation and maintaining privacy.
5	According to the analyses in Table 7, the arrangement of elements within the Baber-Room spaces is such that the most suitable location for receiving wind is at a height of 20 centimeters, encompassing the sleeping area of the Baber room.
6	Unlike modern constructions in Bandar Lengeh, the Baber-Room's windows were strategically placed from the floor level, enhancing the comfort of a night's sleep.
7	Vernacular and handmade materials were used to build the Baber-Room. One such material is the mat, which has been effectively used as a cover in different building orientations to reduce the harsh midday sunlight entry.
	Weaknesses
1	With the advent of mechanical air conditioning systems, such spaces have lost their functionality, and most buildings with Baber-Rooms have been abandoned, either demolished or with all their latticed walls filled in with mortar.

the thermal properties of nano-building materials have a notably positive impact compared to traditional building materials. Barzegar and Sajjadi (2023) explored light and temperature dynamics in traditional Shiraz houses in a related study. Their findings highlighted that using local houses under current conditions often leads to dissatisfaction, as they do not adequately respond to modern needs. This aspect is particularly relevant when comparing traditional houses with the Baber-Room, suggesting that the latter's applicability is restricted to certain favorable weather conditions throughout the year rather than being universally adaptable to contemporary climatic demands, And, as is well known, the Baber-Room is regarded as a unique sort of native architectural space in Hormozgan-Iran, capable of providing comfort to people's lives by using local materials, understanding the environmental conditions, and meeting the cultural needs of society (by creating meeting spaces). All this leads to comfort in human life. There are seven positive points and one weak point (where the use of the Baber-Room was lost due to the usage of mechanical air conditioning equipment), indicating that this area can be used as a new solution to preserve the region's local culture while using modern methods.

The current use of local housing has also led to dissatisfaction and does not adequately address current conditions. This is significant, especially when compared with the Baber-Room, indicating that it is only feasible to use these local spaces under current conditions during certain times of the year when the weather is pleasant and favorable.

The results achieved came from Baber-Rooms in the local architecture of Bandar-Lengeh, which indicated that architects and users have been looking for function and beauty in local architecture under the hot-humid conditions of the region. Therefore, it shows users'/architectures' contemplation and reasoning in the past. Hopefully, this research will provide architectures with a stable structure to achieve and implement these in new constructions. Besides, users should do their best to keep this architecture as a legacy. Another topic for future research is exploring how the Baber-Room can be used in contemporary settings to preserve vernacular culture and architecture.

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INTEGRATION OF CIRCULARITY STRATEGIES INTO ARCHITECTURAL DESIGN THROUGH BIM

INTEGRACIÓN DE ESTRATEGIAS DE CIRCULARIDAD AL DISEÑO ARQUITECTONICO MEDIANTE BIM

INTEGRAÇÃO DE ESTRATÉGIAS DE CIRCULARIDADE AO PROJETO ARQUITETÔNICO POR MEIO DO BIM

Viviana Duran-Navarrete
Arquitecta, Estudiante de Postgrado
Departamento de Diseño y Teoría de la Arquitectura, Facultad Arquitectura, Construcción y Diseño
Universidad del Bío-Bío, Concepción, Chile
https://orcid.org/0009-0007-4927-2858
vduran@egresados.ubiobio.cl (Autora de Correspondencia)

Rodrigo García-Alvarado
Doctor en Representación Arquitectónica, Profesor Titular
Departamento de Diseño y Teoría de la Arquitectura, Facultad Arquitectura, Construcción y Diseño
Universidad del Bío-Bío, Concepción, Chile
https://orcid.org/0000-0003-2216-2388
rgarcia@ubiobio.cl

Mabel Vega-Coloma
Doctora en Ingeniería, Académica
Departamento de Ingeniería en Maderas, Facultad Ingeniería
Universidad del Bío-Bío, Concepción, Chile
https://orcid.org/0000-0003-1599-6747
mvega@ubiobio.cl

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RESUMEN

La industria de la construcción representa gran parte del consumo de recursos naturales, proyectándose el aumento de residuos de construcción y demolición (RCD) a nivel mundial en un 70% al año 2050 si no se toman medidas urgentes. La aplicación de economía circular en la construcción, requiere selección de productos en base a su potencial circular, en la fase de diseño, para optimizar la reutilización y minimizar residuos. Se propone metodología mixta combinando componentes cualitativos, explorando cómo los actores involucrados en la construcción integran, múltiples factores que influyen en la recuperación del material, asignándoles valores porcentuales que reflejan el potencial circular del producto. Esta información cuantitativa, se visualizará gráficamente en BIM (Building Information Modeling), obteniendo cuantificación sintética en porcentaje de RCD. Se compara la circularidad del modelo de estudio, con uno más favorable, y otro menos favorable. Detectándose diferencias sustanciales en la circularidad, y una determinación en porcentaje de RCD, para formular diseños informados.

Palabras clave
diseño circular, recuperación de materiales, escala transición circular, BIM

ABSTRACT

The construction industry represents a large part of the consumption of natural resources, with construction and demolition waste (CDW) projected to increase worldwide by 70% by 2050 if urgent measures are not taken. Applying circular economy in construction requires product selection in the design phase based on their circular potential, optimizing reuse to minimize waste. A mixed methodology is proposed, combining qualitative components and exploring how the actors involved in construction integrate multiple factors that influence the recovery of the material, assigning them percentage values that reflect the circular potential of the product. This quantitative information will be displayed graphically in BIM (Building Information Modeling), obtaining a synthetic quantification of the percentage of CDW. The circularity of the study model is compared with a more favorable one and a less favorable one, detecting substantial differences in circularity and determining the CDW percentage to formulate informed designs.

Keywords
circular economy, materials recovery, circular transition scale, BIM

RESUMO

O setor de construção é responsável por uma grande parte do consumo de recursos naturais, com a projeção de que os resíduos globais de construção e demolição (CDW) aumentem em 70% até 2050, se não forem tomadas medidas urgentes. A aplicação da economia circular na construção exige a seleção de produtos com base em seu potencial circular, na fase de projeto, para otimizar a reutilização e minimizar o desperdício. Propõe-se uma metodologia mista que combina componentes qualitativos, explorando como os atores envolvidos na construção integram vários fatores que influenciam a recuperação de materiais, atribuindo valores percentuais que refletem o potencial circular do produto. Essas informações quantitativas são visualizadas graficamente no BIM (Building Information Modelling), obtendo-se uma quantificação sintética em porcentagem de RCD. A circularidade do modelo de estudo é comparada com um modelo mais favorável e outro menos favorável. São detectadas diferenças substanciais na circularidade e uma determinação em porcentagem de RCD, para formular projetos informados.

Palavras-chave:
projeto circular, recuperação de materiais, escala de transição circular, BIM

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INTRODUCTION

The construction industry's assembly line production system worldwide has led the planet to unsustainable production models (Lacouture, 2013). This model consumes large volumes of raw materials (Fiel, 2022) and generates significant Construction and Demolition Waste (CDW) (Mora, 2021). This has resulted in a 40% depletion of natural materials, 40% of the world's energy consumption, and the loss of 15% of freshwater resources (Akanbia et al., 2018).

According to Kibert (2008), 50% of the waste generated by the construction industry worldwide is due to demolition (Ghisellini et al., 2018), while its indirect impacts are related to the disposal of construction waste (Ossio, 2021). Therefore, the construction industry is crucial for transitioning to a circular economy (CE) (Prieto-Sandoval et al., 2017).

According to a World Bank report, "If urgent measures are not taken, global waste will increase by 70% by 2050" (Climent Salvador, 2021). The objective is to prevent the overexploitation of raw materials and waste before they are produced and implement sustainability and circularity concepts in the design process (Mora, 2021).

Circular Economy seeks sustainable development through collaborative work and the closure of energy and material flows (Mercader Moyano et al., 2019), designing products to be reused and recycled (Climent, 2021). To achieve this, indicators that promote circularity (Corantioquia, 2022) in the design and use of recyclable materials (Potting et al., 2017) must be considered.

Evaluating materials' resilience, focusing on the perception and experience of construction company representatives, can be an innovative method that supports a holistic framework for defining resources' circular potential (Ulgiati, 2018). However, many companies lack the information (Ca et al., 2013) necessary to select the right tools and techniques for their needs (Enshassi et al., 2014).

Integrating circular strategies in the conceptual design through the BIM (Building Information Modeling) Revit software would facilitate the graphic visualization of material circularity, allowing a better choice through an integrated geometry database with numerical data (Climent, 2021).

This research studies and applies circular strategies (CS) using BIM to measure constructive elements' circular potential (Salehabadi & Ruparathna, 2022). It considers factors that help optimize reuse and recycling to minimize the volume of waste and the complexity of recycling materials (Zhang & Jia, 2021).

That is why a simple methodology is reviewed, integrating a perception survey database applied to construction company representatives. These representatives have a holistic knowledge of local values and projects and can converge multiple factors that influence the recovery of materials into a single indicator (Mesa & Esparragoza, 2018). After this, the resulting quantitative information will be integrated into the BIM environment through a generic application for the graphical visualization of the models and synthetic quantification in the percentage of CDW.

METHODOLOGY

The research will adopt a mixed approach that combines qualitative and quantitative components to understand the feasibility of incorporating (CE) from the BIM conceptual design.

Sustainable designers must measure the circular potential of materials using available methods and tools.

Linder et al. (2017) and Prieto-Sandoval et al. (2017) recommend that a circularity metric focuses on measuring circularity, "the recoverable fraction of a product that comes from used products," as a unique attribute of the quality of each material (Lacouture, 2013).

To measure circularity, a proposal from the Report by Potting et al. (2017), which states "to collect semi-quantitative data and compile them into indicators that provide meaningful information, semi-quantitative indicators can be organized into classes; 'red, yellow, green' (Mora, 2021), will be considered.

Based on this, the measurement of the recoverable fraction of the material will be determined in three attributes (Nieroa & Kalbar, 2019), which will define the circular potential: (a) Almost everything is recoverable (b) Some parts are recoverable (c) Almost nothing is recoverable. Information about the materials' circular potentials is obtained through fieldwork, applying a perception survey to the representatives of the construction companies to gain their holistic knowledge of the multiple factors that affect the recovery capacity of a material.

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Table 1. Strategies of circularity. Source: Political report by Potting et al. (2017).

Circular Economy		Circular Strategies	Circular strategies concepts
Increasing circularity	Smarter use and manufacturing of products	R0 Reject	Use the discarded product or its parts in a new product with a different function.
		R1 Rethink Redesign	Make the product use more intensive by sharing products or putting multifunctional products on the market.
		R2 Reduce	Increase efficiency in manufacturing or using products by consuming fewer natural resources and materials.
Rule of thumb: The higher the level of circularity, the fewer natural resources and less environmental pressure	Extend the shelf life of the product and its parts.	R3 Re-Use Recover	Reuse by another consumer of the discarded product that is still in good condition and fulfills its original function.
		R4 Repair	Repair and maintain the defective product to be used for its original function.
		R5 Restore Renew	Restore an old product and update it.
		R6 Remanufactured	Use parts of the discarded product in a new product with the same function.
		R7 Reuse	Using parts of the discarded product or its parts in a new product with a different function.
	Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality.
Linear Economy		R9 Recover	Collect materials or products that have already been used but maintain their usefulness and reintroduce them into the production process.
		R10 Valorize energetically	Incineration of materials with energy recovery.

QUALITATIVE COMPONENT

The qualitative research is adapted to the content analysis, and the survey explores how the players involved in construction conceptualize and understand the meanings of circularity.

PERCEPTION SURVEY STRUCTURE; POTTING TRANSITION SCALE

Known as 10R strategies, this framework will structure the survey (Javier & Xavier, 2019) by measuring the resilience of materials, collecting semi-quantitative data, and compiling them into indicators that provide meaningful information (Table 1).

The CEs, R0 to R2, will not be the subject of study and are not directly related to the implementation phase (Mora, 2021). The research will be defined according to the CEs, R3 to R10.

PERCEPTION SURVEY METHODOLOGY

An expert, a professor at UBB, reviewed the content. The writing and comprehension of pilot survey questions were validated by applying them to three construction companies in the area, different from the sample. The survey questionnaire was supplemented with a definition of CE from the Report by Potting et al. (2017) to pool sample response criteria.

Table 2. Quantification of CDW percentages. Source: Preparation by the authors.

WALL STRUCTURE CUBICATION TABLE								
			A	B	C	D	E	F
HOUSING	ITEM	CONSTRUCTIVE ELEMENTS	VOLUME (m3)	% OF WASTE (%) (c)	(A)*(B) %CDW BY MATERIAL	AVERAGE SPECIFIC WEIGHT (Kg/m3)	(D)*(A) CALCULATION OF TOTAL WEIGHT OF MATERIALS (Kg)	(E)*(B) CALCULATION OF TOTAL WEIGHT OF THE WASTE (Kg)

Table 3. Circular potential cut-off ranges in Revit. Source: Preparation by the authors.

Constructive Item	Material	(c) Almost nothing %	(a) Almost everything %	(b) Some parts %	% Total circular potential (a)+(b)
Data	(Include from the project)	(Include of perception survey results)			(sum total)
	% Cut-off Range	xx			yy
		Max. Low circularity			Min. High circularity

The survey was structured in three categories. The first measures perceptions of materials' resilience. The second is complemented by factors that affect the materials' recovery capacity. The third asks for the interviewee's personal information (Appendix A). These were performed over five days. The author gave a brief verbal introduction and instructions on completing the measuring instrument, resolving doubts, and reading the informed consent form before asking questions.

SAMPLE UNIVERSE

A non-probabilistic sampling method was used to select 10 representative construction companies, covering 67% of the companies in the Province of Arauco with experience in rural social housing projects. The sample is not random; it was chosen from the researcher's professional contacts. For confidentiality reasons, the names of specific companies have been excluded here.

QUANTITATIVE COMPONENT: VALUATION ATTRIBUTES (A), (B), (C)

The multiple factors that influence material recovery are framed in three circular attributes reflecting the frequency of a circular perception;
(a) Almost everything…
(b) Some parts... ... of that fraction of the residual material is recoverable
(c) Almost nothing…
The tabulated values are represented in percentages, facilitating objective interpretation.

Table 4. Traffic light-type cut-off ranges; Revit display. Source: Preparation by the authors.

Circular Indicator	Color Assigned	Cut-off range %
(a) Almost everything	Green	yy% to 100%
(b) Some parts	Yellow	xx+1% to yy-1%
(c) Almost nothing	Red	1% to xx%

The dependent variables include the circularity indicator, the materials' recovery capacity, and the CE, which are independent variables.

Non-recoverable fraction (b)

Percentage of the material that can improve its recoverability, incorporating factors to enhance the design.

Non-recoverable fraction (c)

The tabulated data from the surveys will be used to calculate the weighting percentage of the construction site waste. Together with the specific weight of the materials in the Revit database (Fernández & Raposo, 2022), they will allow determining the recycling weight of each item on site (Table 2), approaching the waste management protocols in Chile; "Roadmap CDW-2035", as in all countries of the European Union; European Directive Standard 2008/98/EC.

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Table 5. Case study materials. Source: Preparation by the Authors.

Constructive Item		Base	Proposal 1	Proposal 2
Structure	walls	2"x3" Partition	Metalcom Partition	Reinforced concrete walls
	roofing	2"x4" Truss 2x2" Girt	Metalcom truss and girt	2"x4" Truss 2x2" Girt
	floor	8cm concrete floor slab	Wooden board	8 cm concrete floor slab
Foundation		Foundation run	30x30x60 concrete sill 3"x8" wooden beam	80x80x40 concrete capstones
Roof		Zinc alum	0.35cm zinc alum tile.	0.35 cm asphalt tile
Interior Finish		Plasterboard (Z.S) Fiber Cement (Z.H)	Wooden board. (Z.S) Fiber Cement (Z.H)	Exposed concrete
Exterior Finish		Fiber cement siding	Tongue-and-groove wood	Fiber cement siding
Windows		4 Aluminum 130x120cm 1 Aluminum 100x100cm 1 Aluminum 60x60cm 1 Aluminum 60x90cm	4 PVC 130x120cm 1 PVC 100x100cm 1 PVC 60x60cm 1 PVC 60x90cm	4 wooden 130x120cm 1 wooden 100x100cm 1 wooden 60x60cm 1 wooden 60x90cm
Doors		1 Solid Wood 90x200cm 5 plywood (placarol) 70cm	1 metallic 90x200cm 5 metallic 85cm	6 solid wood 85x200cm

CUT-OFF RANGES; INTEGRATION TO REVIT

A color will be assigned through the Revit software (Jalaei & Jrade, 2014) to facilitate graphical visualization. The total circular potential of the material will be the result of (a) + (b). The percentage value is proportional to its circularity, while in (c), its percentage is inversely proportional to the circularity of the element. This variable is individualized as the residual material or percentage of CDW (Table 4).

Defining the average of the highest percentages of the total circular potential of the materials through a simple mathematical equation (a)+(b) will give the cut-off range of the highest circularity. The average of the higher percentages of (c) will provide the lowest circularity cut-off range (Table 3).

Each range (Table 3). to be incorporated in the "filter rules" box of the Tutorial step; IV.) should be assimilated to colors according to:

IMPLEMENTATION OF CASE STUDY TO REVIT

A tutorial will be provided on integrating materials' circular potential into Revit software by associating "traffic light"-type indicators (Appendix D). The method's feasibility was verified by consulting two experts in the 3D modeling tool. For this purpose, basic housing was compared with a more favorable proposal 1 and a less favorable proposal 2 (Table 5).

PLANIMETRY OF CASE STUDY

Wooden house of 62.24 m^2, design features in (Figures 1, 2, and 3). The model will be developed with Autodesk Revit.

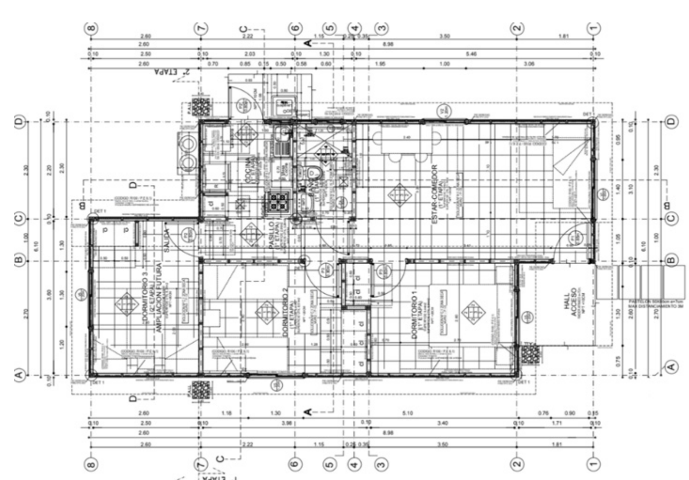

Figure 1. Architecture floor plan, mass construction typology. Source: Preparation by the authors

Figure 2. Main and left side view. Source: Preparation by the authors

Figure 3. Cross-section and right-side view. Source: Preparation by the authors

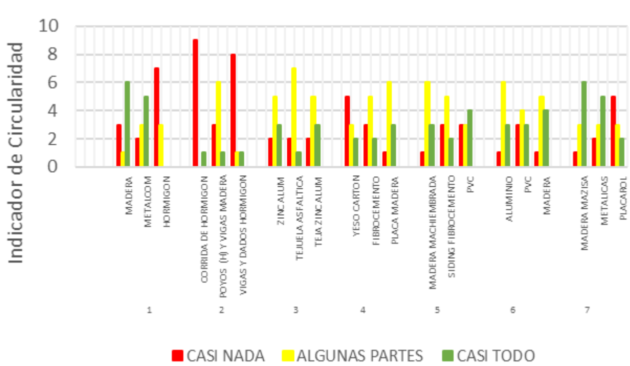

Figure 4. Recover Tabulation. Source: Preparation by the Authors.

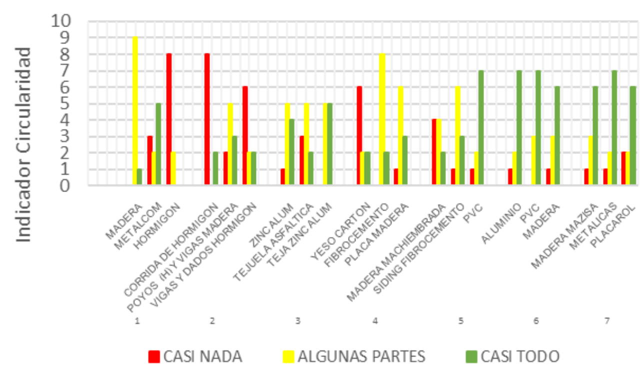

Figure 5. Reuse Tabulation. Source: Preparation by the Authors.

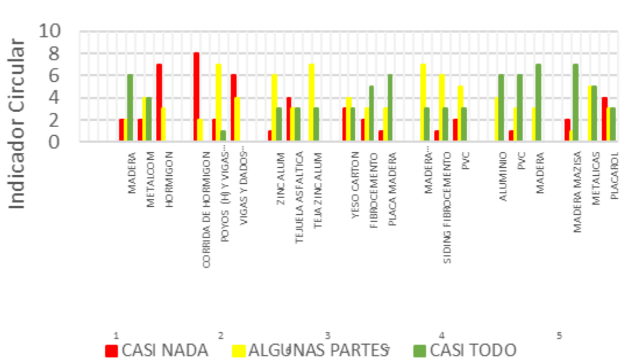

Figure 6. Recycle Tabulation. Source: Preparation by the Authors.

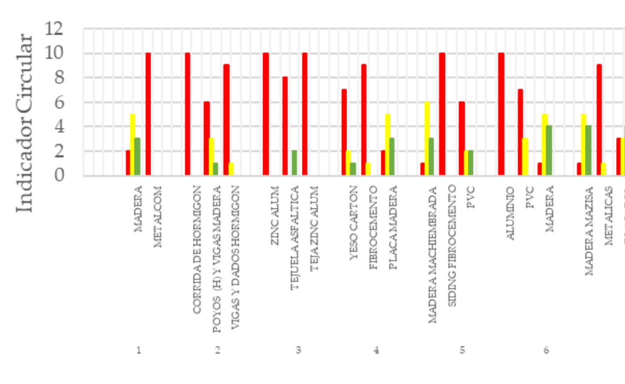

Figure 7. Incinerate Tabulation. Source: Preparation by the Authors.

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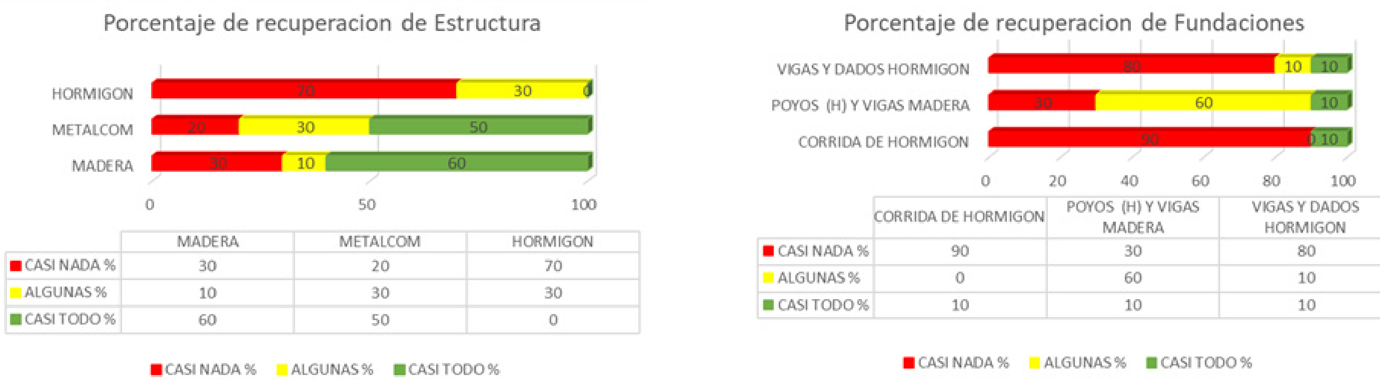


Figure 8. Structure and Foundation. Source: Preparation by the authors.

Figure 9. Roof and Interior Finish. Source: Preparation by the authors.

RESULTS AND DISCUSSION

The companies considered the same concept for the Recover (Figure 4) and Reuse (Figure 5) strategies. It should be noted that concrete in the structure and foundation items has a low percentage of circularity; on the contrary, wood has a high potential for reuse.

Repair and Restore refer to recovering the historical value due to lack of maintenance. The results defined these as non-binding CEs for construction.

Remanufacture. The concept indicates that the CE is not applied in the construction phase, as the votes are inclined to option (c): almost nothing.

Recycle. The CE best known and applied by contractors. We see a tendency toward medium-high circularity. (Figure 6)

The respondents in the Recover, Reuse, and Recycle CE recognize concrete as the heaviest element and elements of lower quality in their composition, such as plasterboard and the placarol (plywood) door, as having less circular potential.

Incinerate. The responses reflect a tendency to avoid incorporating this Strategy (Figure 7). The tendency to incinerate is medium-high only in the alternatives that consider wood.

Given the results, "not all Circular strategies can be inherently sustainable; it requires a previous analysis that defines where to place this strategy....". This analysis found equality between the 100% Recover and Recycle and 57% Recover and Reuse results. Although recycling building materials is common, it requires more energy use, and reuse is value-oriented. Recovery is then considered over recycling (Salehabadi & Ruparathna, 2022), understanding that this occurs only when the material can no longer be recovered.

MEASURING CIRCULARITY

Determining an absolute percentage of recovery for each material is impossible.

Therefore, numerical values are assigned to the answers, translating the ranges of circular attributes into percentages and establishing how much "can be recovered."; (a) Almost everything, (b) Some parts, (c) Almost nothing (Figure 8, Figure 9, Figure 10 y Figure 11).

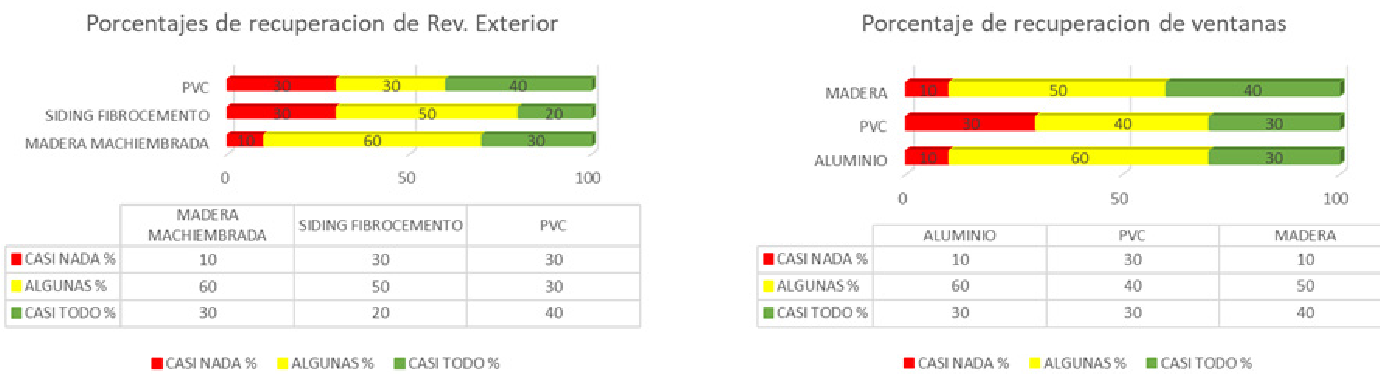


Figure 10. Exterior finish and windows. Source: Preparation by the authors.

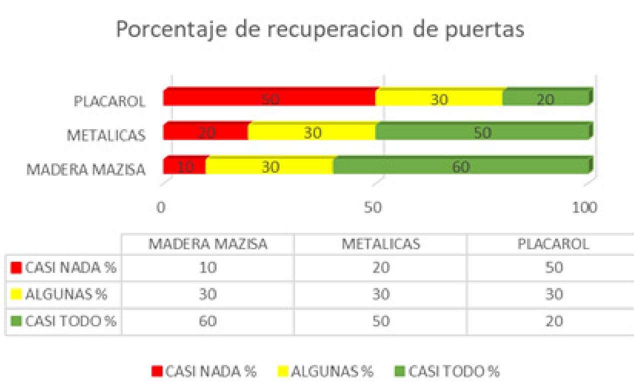


Figure 11. Doors. Source: Preparation by the authors.

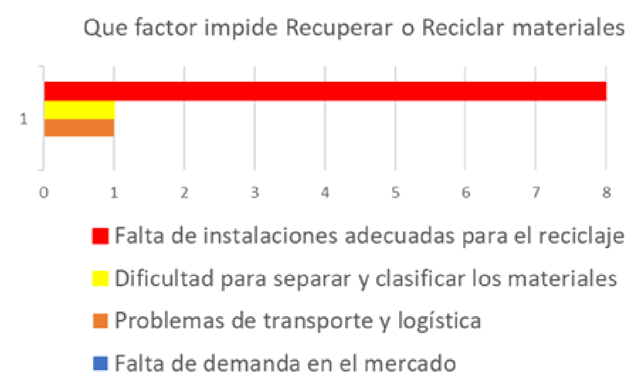


Figure 12. Factors that prevent recycling. Source: Preparation by the authors.

The "traffic light-type" graphic reiterates concrete, placarol (plywood), and plasterboard as the materials with the lowest circularity.

DESIGN FACTORS THAT ENHANCE RECOVERY

The trend in Construction Companies' actions is to include basic factors that influence the resilience of materials. The survey shows a strong trend towards sustainability, both in its incorporation in the design of assemblies, stratification, quality, etc. and in the incorporation of actions in the field of material separation.

The lack of recycling facilities in the area is strongly evidenced (Figure 12).

INTEGRATION OF CUT-OFF RANGES TO REVIT

The total circular potential will be determined as the result of (a) + (b) (Table 6). The average of the highest percentages of the total circular potential of the materials will give the cut-off range of the percentages with the highest circularity. Meanwhile, the average of the higher percentages of (c) will give the cut-off range of the lowest-rated percentages (Table 7).

GRAPHICAL VISUALIZATION IN REVIT AND SYNTHETIC APPROXIMATION.

With Revit's geometric information and the incorporation of the percentages of (c), the volume of the project›s materials and the percentage of CDW emitted by the material are obtained. To meet the goal proposed in the Circular Economy under Construction CDW Roadmap. "At least 30% of the volume of the CDW is recovered: Reuse..." While the goal, by 2035, should reach 70% of the volume of the CDW recovered, as detailed in Table 8.

Thus, the valuation of such materials and/or construction systems should increase by an average of 3.7% by 2025 and 8.65% by 2035.

We analyze housing based on the European Union's policies. By 2020, 70% of the total weight of waste from CDW should be recycled or reused. This gives a weight of 31,257.28 CDW; the 70% should be valued at 21,880.96 CDW by 2020 to meet the proposed goal according to European Directive 2008/98/EC.

The Revit graphic visualization and the database

Table 6. Calculation of cut-off ranges. Source: Preparation by the authors.

Constructive Item	Material	(a) Almost nothing %	(b) Almost everything %	(c) Some parts	Total circular potential
Structure	Wood	30	10	60	70
	Metalcom	20	30	50	80
	Concrete	70	30	0	30
Foundations	Concrete Run	90	0	10	10
	Sills and beams	30	60	10	70
	Beams and concrete capstones	80	10	10	20
Roof	Zinc alum	20	50	30	80
	Asphalt shingle	20	70	10	80
	Zinc alum plate	20	50	30	80
Interior Finish	Plasterboard	50	30	20	50
	Fiber Cement	30	50	20	70
	Wooden board	10	60	30	90
Exterior Finish	Tongue-and-groove wood	10	60	30	90
	Fiber cement siding	30	50	20	70
	PVC	30	30	40	70
Windows	Aluminum	10	60	30	90
	PVC	30	40	30	70
	Wood	10	50	40	90
Doors	Solid wood	10	30	60	90
	Metallic	20	30	50	80
	Placarol	50	30	20	50
% Cut-off Range		48.5			84.2
		Max. Low circularity			Min. High circularity

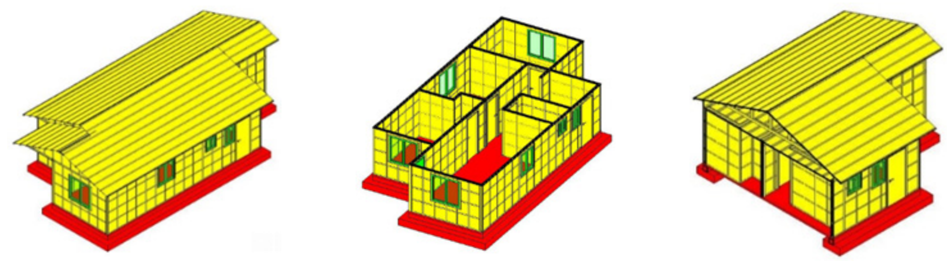
Table 7. Traffic light indicator cut-off ranges. Source: Preparation by the authors.

Circularity Indicator	Color	Value Ranges %
Almost Everything	Green	84% to 100%
Some Parts	Yellow	50% to 83%
Almost Nothing	Red	0% a 49%

Table 8. CDW volume and weight percentage calculation. Source: Preparation by the authors.

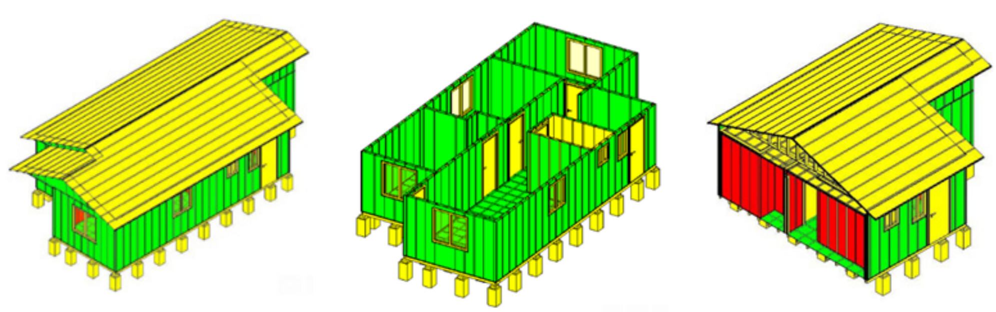
		Roadmap Goal (CORFO, 2020b). Chile.		European Union Regulations	
Model	Total CDW Volume per dwelling (v)*(c)	30% CDW volume by 2025 (v)*0.3	70% CDW volume by 2035 (v)*0.7	CDW Total Weight (p)	70% of the CDW weight by 2020 (p)*0.7
Basic Housing Wooden Structure	14,328	4.2984	10.0296	31257.28	21880.096
Proposal 1 Lightweight structure	2,159	0.6477	1,513	7574.02	5301.814
Proposal 2 Concrete Structure	20,518	6.1743	14.4067	48022.68	33615.876

Table 9. Basic housing. Source: Preparation by the authors.



Basic housing model	Materials	%Total Circular Potential (a)+(b)	Total Volume (v)	Percentage CDW (c)	% CDW by material (v)*(c)	D Total Weight materials (v)*(pe)	CDW Total Weight D*(c)
Structure	Wood	0.7	8.84	0.3	5,64	14319,71	11462,62
Foundation	Concrete run	0.1	8,49	0.9	7,641	20367,36	18330,62
Roof	Zinc alum	0.8	0.3	0.2	0.06	2130.74	426.15
Exterior Fin.	Plasterboard	0.5	0,53	0.5	0,159	640,34	192,1
Interior Fin.	Fiber cement siding	0.7	1.55	0.3	0,755	1604,43	771,71
Windows	Aluminum	0.9	0.18	0.1	0.018	20,35	2,04
Doors	1 wood 5 placarol	0.5	0.19	0.5	0,055	176,39	72,04
Totals			20.08		**14.328%**	39259.32	**31257.28**

Table 10. Proposal 1. Source: Preparation by the authors.



Proposed Model 1	Materials	%Total Circular Potential (a)+(b)	Total Volume (v)	Percentage CDW (c)	% CDW by material (v)*(c)	D Total Weight materials (v)*(pe)	CDW Total Weight D*(c)
Structure	Metalcom	0.8	3.81	0.2	0.717	22257.53	4430.73
Foundation	Concrete sills	0.7	3.55	0.3	1.065	8511.6	2553.47
Roof	Zinc alum tile	0.8	0.3	0.2	0.06	2130.74	426.15
Exterior Fin.	Tongue-and-groove wood	0.9	0.54	0.1	0.054	352.57	35.26
Interior Fin	Wooden boards	0.9	1.51	0.1	0.171	928.4	123.34
Windows	PVC	0.7	0.18	0.3	0.054	16.28	4.88
Doors	Metallic	0.8	0.19	0.2	0.038	0.93	0.09
	Totals		10.08		**2.159%**	34198.05	**7573.92**

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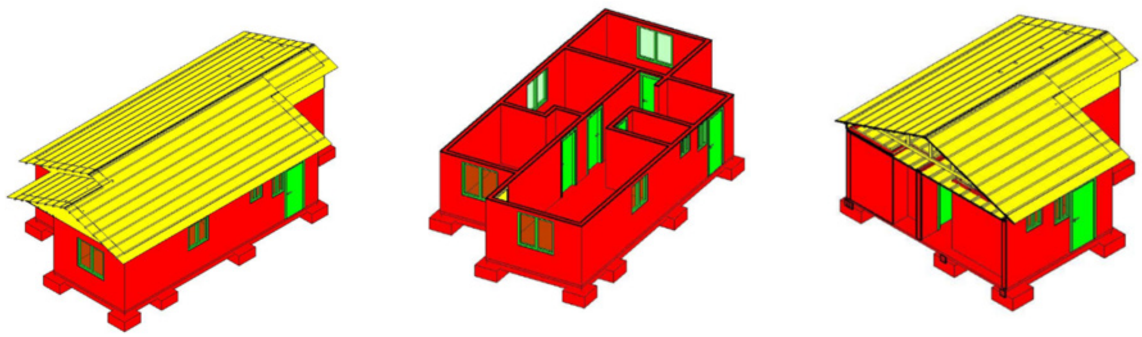
Table 11. Proposal 2. Source: Preparation by the authors.



Proposed Model 2	Materials	%Total Circular Potential (a)+(b)	Total Volume (v)	Percentage CDW (c)	% CDW by material (v)*(c)	D Total Weight materials (v)*(pe)	CDW Total Weight D*(c)
Structure	Reinforced concrete	0.3	20.89	0.9	17.553	46352.82	40904.97
Foundation	Concrete Capstones	0.3	3.58	0.8	2.864	8601.6	6881.28
Roof	Asphalt shingle	0.8	0.3	0.2	0.06	600.21	120.04
Exterior Fin.			0.09	0.3	0.027	107.22	32.17
Windows	Wood	0.9	0.18	0.1	0.018	15.47	1.55
Doors	Wood	0.9	0.19	0.5	0.059	193.08	82.67
Totals			25.23		20.581%	55870.4	48022.68

(Table 9) show that the structure and foundations, by their volume and weight, generate the highest CDW, followed by the roof and then the Interior Finish. These are defined as the main items that must improve their selection and factors that allow their recovery.

Proposal 1 fails to eliminate 84.93% of CDW compared to the base case. The choice of materials in the foundations is complemented to reduce the volume of heavy materials and include removable systems, increasing the recovery potential of the materials (Table 10).

Regarding the CDW volume of the base, the volume of proposal 2 is 30% higher. The low level of circularity in the graph, where structure and foundation are displayed in red (Table 11), is corroborated.

When comparing the base model with the most favorable and another less favorable one, it was found that the methodology detects clear trends between the different construction systems analyzed with a graphical visualization of the models and a synthetic quantification of the percentage of CDW.

The approaches to the national and international standards allow us to highlight the gap in the construction sector's circular transition.

REFLECTIONS OF THE USERS

As a BIM Modeler in project planning and coordination, a recyclability template is a valuable tool that adds value to design in construction. Implementing this tool in the Revit software would improve the use of sustainable resources in construction planning.

DISCUSSION

This research seeks to overcome the lack of knowledge and/or technological integration by offering an experience-based approach to assess the resilience of resources in an accessible way in construction projects.

Incorporating CE through the qualification of sustainable attributes of materials is effective for construction companies. Multiple data are integrated into an indicator that thoroughly evaluates the CE. The experience of the construction companies provides holistic information integrated into the Revit software database through Tutorial, which provides graphical visualization.

The methodology supports the Circular measurement using significant indicators (Potting et al., 2017). This approach simplifies the transition to greater circularity (Calzolari & Genovese, 2022). The objective is to provide a more straightforward but more rigorous and accessible indicator for project development actors by bringing CE closer to designers in the initial design stages.

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The BIM platform provides graphical results, facilitating the comparison of solutions and the making of informed decisions; in combination of BIM with information provided by the actors involved in the process opens new possibilities to promote sustainability in construction and facilitate the implementation of CE strategies in projects, associating the low adoption of circular economy tools to their complexity and lack of information (Dufrene et al., 2013).

CONCLUSION

The integration of CE in the conceptual design stage using BIM in the context of housing construction was explored. The research included the leading players of the construction process to evaluate the circularity potential of different construction elements and their application in a BIM housing model.

The assigning of numerical values to the survey determined the fluctuation of percentage ranges, obtaining high average and low circularity, where the average range allows incorporating factors that improve circularity through the use of removable connections, pins, bolts, etc.

When complementing this information with Revit's geometric data, it was seen that the structure and the foundation define the highest percentage of the CDW by concentrating on the highest volume and weight of the house. The base house has a 9.35% CDW volume, the house of Proposal 1 has a 2.15% CDW volume, while Proposal 2, structured in concrete, has a 15.63% CDW volume when analyzing the values for the fulfillment of the 2025 goal of the 2025 Roadmap.

On analyzing the alternatives by construction item, it is evident that involving concrete in the items, low-quality materials such as sheet metal doors, or fragile materials such as plasterboard increases the percentage of low circularity. Conversely, incorporating wood in any format increases the high circulation valorization percentage.

In lightweight materials, the high circular potential is strongly enhanced with the percentage of the partial potential of the material, generating a greater opportunity to improve the recovery of these materials by incorporating systems that favor the recovery of the project's parts. In short, (b) represents the potential to maximize recovery through design.

Despite the study's contributions, it has limitations since it was based on a qualitative appreciation of the materials through surveys without a detailed specification of the factors considered to evaluate the elements' resilience. It is suggested that future research integrates factors such as assemblies and fixings into Revit modeling for a more complete assessment of the circular potential.

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Objeto singular Columna