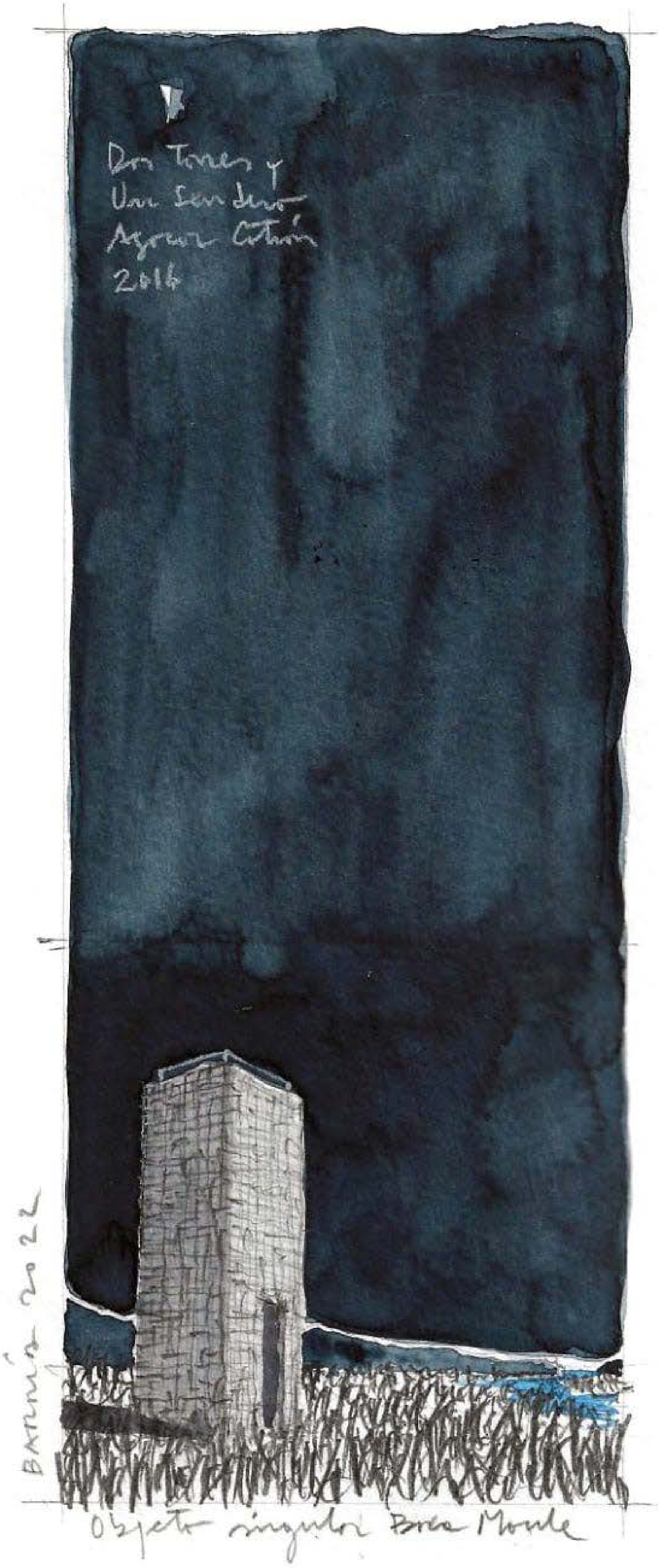

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Editorial
Maureen Trebilcock-Kelly, Alexis Pérez-Fargallo
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EDITORIAL

El año 2023 ha marcado un hito climático alarmante con las temperaturas más elevadas desde que existen registros climáticos. Noviembre, en particular, ha alcanzado la cifra más alta para dicho mes con 2°C por encima del nivel preindustrial, elevándose la media global anual en 1,25°C por encima de la media preindustrial. Estos datos evidencian que estamos próximos a sobrepasar el umbral de 1,5°C fijado en el Acuerdo de París[1] para 2045, previendo que este límite se supere en 2034[2].

Siete años después de la implementación del Acuerdo, observamos un creciente compromiso global, con países, regiones, ciudades y empresas estableciendo objetivos de carbono neutralidad. Sin embargo, en 2022 se emitieron 53,8 Gt CO2eq a nivel mundial, lo que supuso un 2,3% más que en 2019, año anterior a la pandemia Covid-19[3]. China, Estados Unidos, India, la UE27, Rusia y Brasil emitieron en 2022 el 61,6% de las emisiones de Gases de Efecto Invernadero del mundo.

El último Informe publicado por La Alianza Mundial para Edificios y Construcción[4] (GlobalABC) sobre el estado mundial de los edificios revela una realidad nada halagüeña. En 2021, el sector edificatorio fue el responsable de más del 37% de las emisiones de CO2 y del 34% de la demanda de energía, mostrando un repunte negativo respecto de 2020 y con un crecimiento promedio del 1% anual desde 2015.

Según Breakthrough Agenda Report 2023[5], lograr cero emisiones netas para 2050 requiere que todos los edificios nuevos sean cero netos a partir de 2030, representando actualmente menos del 5%. Además, la intensidad energética del sector debe reducirse en un 41% para 2030, sin embargo, hasta 2023 tan solo ha disminuido alrededor de un 6% en comparación 2015.

A pesar de la tendencia actual para encaminarse a la consecución de cero emisiones netas de carbono para 2050, el crecimiento global de superficie construida está compensando los esfuerzos enfocados en aumentar la eficiencia y descarbonizar el sector.

El 6 de diciembre de 2023, en la COP28 de los Emiratos Árabes Unidos, se lanzó oficialmente Buildings Breakthrough[6], el evento fue titulado "*Buildings and construction for sustainable cities: New key partnerships for decarbonisation, adaptation and resilience*". Buildings Breakthrough es una plataforma de colaboración internacional codirigida por Francia y el Reino de Marruecos y bajo la coordinación de GlobalABC. Actualmente reúne a más de 25 países para trabajar juntos en desbloquear acciones en el sector de la construcción bajo el objetivo que las edificaciones con emisiones casi nulas y los edificios resilientes sean la norma o estándar para 2030. Según esta plataforma los "*edificios con emisiones casi nulas*" son construcciones concebidas con un enfoque de evaluación del ciclo de vida completo, de alta eficiencia energética y con una baja huella de carbono; mientas que los "*edificios resilientes*" son construcciones que integran especificaciones relacionadas con el clima futuro en su diseño, construcción y operación y mantenimiento.

Mientras que trabajamos en códigos, financiamiento y adaptación del sector de la construcción para lograr edificios de emisiones casi nulas y resilientes, el tiempo se

1 El Acuerdo de París es un tratado internacional sobre el cambio climático jurídicamente vinculante. Fue adoptado por 196 Partes en la COP21, el 12 de diciembre de 2015 y entró en vigor el 4 de noviembre de 2016. Su objetivo es limitar el calentamiento mundial, en comparación con los niveles preindustriales, por debajo de 2 y, preferiblemente bajo 1,5 grados centígrados.

2 https://climate.copernicus.eu/weve-lost-19-years-battle-against-global-warming-paris-agreement

3 Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muntean, M., Schaaf E., Becker, W., Monforti-Ferrario, F., Quadrelli, R., Risquez Martin, A., Taghavi-Moharamli, P., Köykkä, J., Grassi, G., Rossi, S., Brandao De Melo, J., Oom, D., Branco, A., San-Miguel, J., Vignati, E., GHG emissions of all world countries, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/953322, JRC134504.

4 https://globalabc.org/our-work/tracking-progress-global-status-report

5 IEA, IRENA & UN Climate Change High-Level Champions (2023), Breakthrough Agenda Report 2023, IEA, Paris https://www.iea.org/reports/breakthrough-agenda-report-2023, License: CC BY 4.0

6 https://globalabc.org/our-work/fostering-collaboration

acorta dramáticamente para mantener las temperaturas globales por debajo de 1,5°C en comparación con el promedio preindustrial. Además, enfrentamos riesgos significativos para la descarbonización del sector, como conflictos armados, volatilidad de los precios mundiales de la energía, incremento del costo de vida que enfrentan las economías, aumento de las tasas de interés, resistencia de los productores de energías fósiles, como se evidenció en la COP 28, junto con los desafíos inherentes al propio cambio climático, que incluyen alteraciones climáticas, fenómenos extremos, escasez hídrica, incendios, riesgo de inundaciones, entre otros.

Un ejemplo concreto de estos desafíos es el impacto que las sequías tienen en las fuentes de energía hidroeléctrica en América Latina, región donde esta fuente abastece la mitad de las necesidades de electricidad[7]. Durante 2022, la caída de la producción hidroeléctrica en la cuenca del Paraná-La Plata, obligó al uso de combustibles fósiles, contrarrestando así el impacto de las medidas de transición energética destinadas a lograr emisiones cero[8].

Abordar estos desafíos requiere una combinación de innovación en diseño, tecnología y prácticas de construcción y urbanísticas, junto con políticas gubernamentales que fomenten la sostenibilidad y la resiliencia climática.

En este contexto, resulta fundamental que los gobiernos nacionales, regionales y locales establezcan códigos y estándares de construcción para alcanzar la carbono neutralidad en el menor tiempo posible. No obstante, este proceso debe ir de la mano con un aumento significativo en la inversión destinada a la eficiencia energética, así como con iniciativas que impulsen la reducción de emisiones de CO2 a lo largo de toda la cadena de valor, respaldando, al mismo tiempo, la implementación de prácticas vinculadas a la economía circular.

Desde la perspectiva de la Revista Hábitat Sustentable, consideramos necesario intensificar nuestros esfuerzos de investigación en el ambiente construido, generando materiales, soluciones, sistemas constructivos, diseños, tecnologías, estrategias prácticas carbono neutrales. Además, abogamos por la importancia del aporte de los académicos e investigadores, como desarrolladores de conocimiento, al impulso de hojas de ruta, políticas, códigos y estándares que conduzcan a un sector edificatorio y de construcción sostenible, cero carbono y resiliente.

7 https://www.iea.org/reports/climate-impacts-on-latin-american-hydropower/climate-impacts-on-latin-american-hydropower

8 https://library.wmo.int/viewer/66322?medianame=1322_State_of_the_Climate_in_LAC_2022_es_#page=5&viewer=picture&o=bookmark&n=0&q=

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EDITORIAL

2023 has marked an alarming climate milestone, with the highest temperatures since climate records began. November, in particular, reached its highest-ever figure, 2°C above pre-industrial levels, raising the annual global average to 1.25°C above the pre-industrial average. These data show that we are close to exceeding the 1.5°C threshold set in the Paris Agreement[1] for 2045, currently predicting that this will be exceeded in 2034[2].

Seven years after the Agreement's implementation, we have seen a growing global commitment, with countries, regions, cities, and companies setting carbon neutrality targets. However, 53.8 Gt CO_2eq was emitted globally in 2022, 2.3% more than in 2019, the year before the Covid-19 pandemic[3], with China, the United States, India, the EU27, Russia, and Brazil emitting 61.6% of the world's greenhouse gas emissions.

In the latest report published by The Global Alliance for Buildings and Construction[4] (GlobalABC), the state of the world's buildings reveals an unflattering reality. In 2021, the building sector was responsible for more than 37% of CO_2 emissions and 34% of energy demand, a negative rebound compared to 2020, with an average yearly growth of 1% since 2015.

According to the Breakthrough Agenda Report 2023[5], achieving net zero emissions by 2050 requires all new buildings to be net zero from 2030, when currently less than 5% are. In addition, the sector's energy intensity must be reduced by 41% by 2030. However, until 2023, it has only decreased by about 6% compared to 2015.

Despite the current trend towards achieving net zero carbon emissions by 2050, the global growth of the built surface area is offsetting the efforts to increase efficiency and decarbonize the sector.

On December 6th, 2023, at the COP28 in the United Arab Emirates, Buildings Breakthrough was officially launched[6]; the event was titled "*Buildings and Construction for Sustainable Cities: New Key Partnerships for Decarbonization, Adaptation, and Resilience.*" Buildings Breakthrough is an international collaboration platform co-managed by France and the Kingdom of Morocco and coordinated by GlobalABC. It currently has more than 25 countries working together to unlock actions in the construction sector under the goal that buildings with almost zero emissions and resilient buildings become the norm or standard by 2030. According to this platform, "*buildings with almost zero emissions*" are constructions conceived with an evaluation approach of their complete life cycle, high energy efficiency, and low carbon footprint. Meanwhile, "*resilient buildings*" integrate future climate specifications in their design, construction, operation, and upkeep.

While we work on codes, financing, and adaptation of the construction sector to achieve near-zero emissions and resilient buildings, time is dramatically short to keep global temperatures below 1.5°C compared to the pre-industrial average. In addition, we face significant risks for the sector's decarbonization, such as armed conflicts, volatility of world energy prices, an increase in the cost of living faced by economies, a rise in interest rates, and reticence of fossil energy producers, as evidenced

1 The Paris Agreement is a legally binding international climate change treaty. 196 Parties at COP21 adopted it on December 12th, 2015, and came into force on November 4th, 2016. Its goal is to limit global warming, compared to pre-industrial levels, to below 2°C and, preferably, under 1.5°C.

2 https://climate.copernicus.eu/weve-lost-19-years-battle-against-global-warming-paris-agreement

3 Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muntean, M., Schaaf E., Becker, W., Monforti-Ferrario, F., Quadrelli, R., Risquez Martin, A., Taghavi-Moharamli, P., Köykkä, J., Grassi, G., Rossi, S., Brandao De Melo, J., Oom, D., Branco, A., San-Miguel, J., Vignati, E., GHG emissions of all world countries, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/953322, JRC134504.

4 https://globalabc.org/our-work/tracking-progress-global-status-report

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6 https://globalabc.org/our-work/fostering-collaboration

at COP 28, along with the challenges inherent in climate change itself, which include climatic alterations, extreme phenomena, water scarcity, fires, flood risk, among others.

A concrete example of these challenges is the impact of droughts on hydropower sources in Latin America, a region where this source supplies half of the electricity needs[7]. In 2022, the drop in hydroelectric production in the Paraná-La Plata basin forced the use of fossil fuels, thus counteracting the impact of energy transition measures aimed at achieving zero emissions[8].

Addressing these challenges requires a combination of innovation in design, technology, construction, and urban planning practices, along with government policies that foster sustainability and climate resilience.

In this context, national, regional, and local governments must establish building codes and standards to achieve carbon neutrality quickly. However, this process must go hand in hand with a significant increase in investment targeting energy efficiency, as well as initiatives that promote the reduction of CO_2 emissions throughout the entire value chain, supporting, at the same time, the implementation of practices linked to the circular economy.

From the perspective of Hábitat Sustentable, we consider it necessary to intensify our research efforts in the built environment, generating carbon-neutral materials, solutions, construction systems, designs, technologies, and practical strategies. In addition, we advocate for the importance of the contribution of academics and researchers as knowledge developers for promoting roadmaps, policies, codes, and standards that lead to a sustainable, zero-carbon, and resilient building and construction sector.

7 https://www.iea.org/reports/climate-impacts-on-latin-american-hydropower/climate-impacts-on-latin-american-hydropower

8 https://library.wmo.int/viewer/66322?medianame=1322_State_of_the_Climate_in_LAC_2022_es_#page=5&viewer=picture&o=bookmark&n=0&q=

EDITORIAL

O ano de 2023 foi um marco climático alarmante, com as temperaturas mais altas desde que os registros climáticos são mantidos. Novembro, em particular, atingiu o valor mais alto para esse mês, com 2°C acima do nível pré-industrial, elevando a média global anual em 1,25°C acima da média pré-industrial. Esses dados mostram que estamos próximos de ultrapassar o limite de 1,5°C estabelecido no Acordo de Paris[1] para 2045, com a expectativa de que esse limite seja ultrapassado em 2034[2] .

Sete anos após a implementação do Acordo, vemos um compromisso global crescente, com países, regiões, cidades e empresas estabelecendo metas de neutralidade de carbono. No entanto, 53,8 Gt CO_2eq foram emitidos globalmente em 2022, o que representou 2,3% a mais do que em 2019, o ano anterior à pandemia de Covid-19[3]. A China, os Estados Unidos, a Índia, a UE27, a Rússia e o Brasil emitiram 61,6% das emissões mundiais de gases de efeito estufa em 2022.

O último relatório publicado pela Global Alliance for Buildings and Construction[4] (GlobalABC) sobre o estado dos edifícios do mundo revela uma realidade sombria. Em 2021, o setor de construção foi responsável por mais de 37% das emissões de CO_2 e 34% da demanda de energia, mostrando uma recuperação negativa em relação a 2020 e um crescimento médio de 1% ao ano desde 2015.

De acordo com o Breakthrough Agenda Report 2023[5] , para atingir zero emissões líquidas até 2050, é necessário que todos os novos edifícios tenham zero emissões líquidas a partir de 2030, o que atualmente representa menos de 5%. Além disso, a intensidade energética do setor deve ser reduzida em 41% até 2030, mas até 2023 ela só diminuiu cerca de 6% em relação a 2015.

Apesar da tendência atual de se chegar a emissões líquidas zero de carbono até 2050, o crescimento global da área útil está compensando os esforços para aumentar a eficiência e descarbonizar o setor.

Em 6 de dezembro de 2023, na COP28, nos Emirados Árabes Unidos, foi lançado oficialmente o Buildings Breakthrough[6]. O evento foi intitulado "Buildings and construction for sustainable cities: New key partnerships for decarbonisation, adaptation and resilience". O Buildings Breakthrough é uma plataforma de colaboração internacional co-liderada pela França e pelo Reino do Marrocos e coordenada pela GlobalABC. Atualmente, ela reúne mais de 25 países para trabalhar em conjunto e desencadear ações no setor de construção com o objetivo de tornar os edifícios com emissão quase zero e resilientes a norma ou o padrão até 2030. De acordo com essa plataforma, "*edifícios com emissão quase zero*" são edifícios projetados com uma abordagem de avaliação completa do ciclo de vida, alta eficiência energética e baixa pegada de carbono, enquanto "*edifícios resilientes*" são edifícios que integram futuras especificações relacionadas ao clima em seu projeto, construção, operação e manutenção.

À medida que trabalhamos nos códigos, no financiamento e na adaptação do setor de construção para obtermos edifícios resilientes e com emissões quase nulas, o prazo

1 O Acordo de Paris é um tratado internacional juridicamente vinculativo sobre mudanças climáticas. Ele foi adotado por 196 Partes na COP21 em 12 de dezembro de 2015 e entrou em vigor em 4 de novembro de 2016. Seu objetivo é limitar o aquecimento global, em comparação com os níveis pré-industriais, a menos de 2 e, de preferência, a menos de 1,5 graus Celsius.

2 https://climate.copernicus.eu/weve-lost-19-years-battle-against-global-warming-paris-agreement

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6 https://globalabc.org/our-work/fostering-collaboration

para mantermos as temperaturas globais abaixo de 1,5 °C em comparação com a média pré-industrial está diminuindo drasticamente. Além disso, enfrentamos riscos significativos para a descarbonização do setor, como conflitos armados, volatilidade dos preços globais de energia, aumento do custo de vida enfrentado pelas economias, aumento das taxas de juros, resistência dos produtores de energia fóssil, conforme evidenciado na COP 28, juntamente com os desafios inerentes à própria mudança climática, incluindo perturbações climáticas, eventos extremos, escassez de água, incêndios, risco de inundações, entre outros.

Um exemplo concreto desses desafios é o impacto que as secas têm sobre as fontes de energia hidrelétrica na América Latina, uma região onde a energia hidrelétrica supre metade das necessidades de eletricidade[7]. Durante o ano de 2022, a queda na produção de energia hidrelétrica na bacia do Paraná-La Plata forçou o uso de combustíveis fósseis, neutralizando assim o impacto das medidas de transição energética destinadas a atingir zero emissões[8].

Para enfrentar esses desafios, é necessária uma combinação de inovação em design, tecnologia e práticas urbanas e de construção, juntamente com políticas governamentais que promovam a sustentabilidade e a resiliência climática.

Nesse contexto, é essencial que os governos nacionais, regionais e locais estabeleçam códigos e padrões de construção para alcançar a neutralidade de carbono no menor tempo possível. No entanto, esse processo deve ser acompanhado de um aumento significativo no investimento em eficiência energética, bem como de iniciativas para promover reduções de emissões de CO_2 ao longo de toda a cadeia de valor, apoiando a implementação de práticas de economia circular.

Sob a perspectiva da Revista Hábitat Sustentable, consideramos necessário intensificar nossos esforços de pesquisa no ambiente construído, gerando materiais, soluções, sistemas de construção, projetos, tecnologias e estratégias práticas neutras em carbono. Além disso, defendemos a importância da contribuição de acadêmicos e pesquisadores, como desenvolvedores de conhecimento, para a promoção de roteiros, políticas, códigos e padrões que levem a um setor de construção sustentável, com zero carbono e resiliente.

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7 https://www.iea.org/reports/climate-impacts-on-latin-american-hydropower/climate-impacts-on-latin-american-hydropower

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GREEN AIRPORT, CONCEPT AND GENERAL DEVELOPMENT FRAMEWORK

AEROPUERTO VERDE, CONCEPTO Y MARCO GENERAL DE DESARROLLO

AEROPORTO VERDE, CONCEITO E QUADRO GERAL DE DESENVOLVIMENTO

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RESUMEN

Los aeropuertos de todo el mundo están aumentando sus esfuerzos para reducir los impactos que generan en el medioambiente mediante la aplicación de sistemas de gestión ambiental. Esta línea de actuación de la industria aeroportuaria, que no lleva más de quince años, tiene el objetivo de transformar el aeropuerto en lo que se denomina 'aeropuerto verde'. Este se entiende como aquel aeropuerto que tanto su diseño como operación y administración se llevan a cabo de tal manera que su impacto ambiental es el mínimo posible, haciendo su gestión de carácter sostenible. Entonces, en el presente artículo se presenta un marco general de desarrollo del concepto, junto con un análisis de los procesos operativos de los aeropuertos que afectan negativamente al medio ambiente. A partir de lo anterior se sugieren políticas, estrategias y procesos de gestión que permitan minimizar o anular dichos efectos negativos en el entorno aeroportuario con el propósito de acercarlo hacia el concepto de 'aeropuerto verde'.

Palabras clave
aeropuerto verde, gestión ambiental de aeropuertos, aeropuertos sustentables

ABSTRACT

Airports around the world are increasing their efforts to reduce their environmental impacts by implementing environmental management systems. This line of action of the airport industry, which has been in place for no more than fifteen years, aims to transform the airport into what is called a "green airport." This is understood as an airport whose design, operation, and administration are carried out in such a way that its environmental impact is as low as possible, making its management sustainable. Therefore, this article presents a general framework for developing the concept, along with an analysis of airport operational processes that negatively affect the environment. Based on this, policies, strategies, and management processes are suggested that allow minimizing or canceling these adverse effects on the airport environment to bring it closer to the concept of a "green airport."

Keywords
green airport, environmental management of airports, sustainable airports

RESUMO

Os aeroportos de todo o mundo estão aumentando seus esforços para reduzir seus impactos ambientais por meio da implementação de sistemas de gestão ambiental. Essa linha de ação do setor aeroportuário, que está em vigor há não mais de quinze anos, tem por objetivo transformar o aeroporto no que é conhecido como "aeroporto verde". Ele é entendido como um aeroporto cujo projeto, operação e administração são realizados de forma que seu impacto ambiental seja o mínimo possível, tornando sua gestão sustentável. Portanto, este artigo apresenta uma estrutura geral para o desenvolvimento do conceito, bem como uma análise dos processos operacionais dos aeroportos que afetam negativamente o meio ambiente. Com base nisso, são sugeridas políticas, estratégias e processos de gerenciamento para minimizar ou cancelar esses efeitos negativos no ambiente do aeroporto, de modo a aproximá-lo do conceito de um "aeroporto verde".

Palavras-chave:
aeroporto verde, gestão ambiental de aeroportos, aeroportos sustentáveis

INTRODUCTION

Airports are one of the pillars of the global aviation industry. However, with their greenhouse gas emissions, they are not only significant contributors to the climate change that the world is currently experiencing (Postorino & Mantecchini, 2014), but also generate a wide variety of environmental impacts that affect both the physical environment and the health of communities that live in the vicinity of air terminals.

Nowadays, sustainability plays a central role in airport development programs, and growing environmental concerns demand that airport developments and operations are ecologically sustainable and that the industry is sustainable (Kumar et al., 2020; Votsi et al., 2014). Likewise, the global demand for air transport is growing after the COVID-19-imposed restrictions of 2020 and 2021. This means airports must grow and expand their capacity to absorb the expected mid and long-term demand. However, despite the common belief, it is not the financing or availability of land that slows down airport growth, but rather the environmental consequences of their infrastructure expansion that pose a challenge to their development (Ferrulli, 2016).

All this makes it clear that airport environmental sustainability is an emerging global concern (Korba et al., 2022). In this vein, the Airport Council International (ACI) – the international organization for the world's commercial airports - defines airport sustainability as a holistic approach to an airport's management to ensure its economic viability, operational efficiency, conservation of natural resources, and social responsibility (Airports Council International Europe, 2019). Therefore, airport sustainability can only be achieved with the right balance between socio-economic objectives within the limits imposed by the surroundings. This idea underlies the objective of this article, which is to present, from a holistic point of view, the concept and principles of a green airport and the general development framework behind the transformation into a green airport.

METHODOLOGY

The systematic mapping method was used for this work. This is the process of identifying, categorizing, and analyzing existing literature relevant to a given research topic (Carrizo & Moller, 2018; Salama et al., 2017). This review aims to show an overview of the related scientific field, in this case, that of green airports. This systematic mapping is done in three basic blocks: (a) first, defining the search, where the research question, scope of the review, inclusion/exclusion criteria, and finally, search chain, are determined; (b) the search is then done; and (c) third, the analysis and discussion of the results.

As far as the definition of the search is concerned, the research questions are those related to the fundamentals of the 'green airport' concept, namely: what are they or how are they defined? What are their development criteria? How are the related indicators managed? Is there a model or standard to transform an airport into a green one?

As for the scope of the review, it was done mainly between 2006 and 2023 (both inclusive). The argument behind this is that the 'green airport' concept was proposed for the first time in 2006. However, previous scientific literature that published works on 'environmentally sustainable airports' was also considered.

The review was carried out using a bibliographic search in the following digital catalogs: ScienceDirect, IEEE Xplore, Taylor & Francis, Springer, Wiley, SAGE, and JSTOR, for which the following descriptors were used: green airport, environmentally sustainable airports, sustainable airport construction, sustainable air operations, airport environmental impact, airport environmental mitigation, airport and climate change, airport environmental management, green airport accreditation.

On the other hand, the following inclusion/exclusion criteria were applied in the filtering process:

(a) all scientific publications that were only related to the concept of green airports were included;
(b) studies edited in English and Spanish were included;
(c) all studies that proposed guidelines and methodologies for achieving green airports were included;
(d) case studies were included as long as they provided a related conceptual framework and concrete, measurable, and comparable results;
(e) articles without a research design and a well-defined research question were excluded;
(f) third-party reviews were excluded;
(g) review papers were excluded;
(h) works on opinion polls or similar were excluded;
(i) technical reports and/or studies without a solid scientific basis were excluded;
(j) any 'grey literature' that did not have a solid,

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rigorous, and formal theoretical foundation was excluded.

Two review filters were applied regarding the search: (a) the review of the article title and abstract and (b) a review of the full text.

Finally, the last step in the methodology is to present, contextualize, and analyze all the literature found and chosen, following the criteria to develop a green airport. This analysis was segmented by criteria to define a green airport's planning, construction, evolution, and management. These criteria, in turn, are discriminated by concepts and/or indicators directly related to an airport's different operational and management aspects. This segmentation in the analysis is necessary due to airports' tremendous operational complexity.

RESULTS AND DISCUSSION

THEMATIC MAPPING

First of all, and as a result of the extensive bibliographic review, a table is presented that synthesizes the review's thematic and/or concept mapping (Table 1). The description of the results, i.e., the categorization of the environmental impacts and corresponding mitigation strategies, will follow the pattern defined in Table 1.

DEFINITION

A green airport is one that has been designed, and both its operation and administration are run in such a way that its environmental impact is as low as possible to make its management sustainable (Airports Council International Europe, 2015; Ferrulli, 2016) and whose technological setup aims to ensure that all resources are used and managed in the most efficient way possible to generate the least environmental impact. To do this, the airport applies intelligent, collaborative, dynamic, and automated systems capable of responding to the daily needs of all its stakeholders.

In this line, a green airport should contemplate the following actions (Dalkiran et al., 2022; Kilkis & Kilkis, 2016):

a. Explore the different technological advances to improve energy efficiency to reduce consumption.
b. Favor the production of energy using renewable energy sources.
c. Collaborate with airport operators and concessionaires to develop and implement these measures.
d. Evaluate the feasibility, effectiveness, and profitability of these technologies and new operating procedures.
e. Validate that the commissioning of the different actions guarantees the operability and security of the airport.

Table 1: Thematic mapping of the literature review, segmented by an association between the environmental impact generated and the strategy used. Source: Preparation by the author.

Environmental strategy (considering the impact generated)	References
Noise mitigation measures for service vehicles and aircraft.	Fyhri & Aasvang (2010); Meister & Donatelle, (2000); Babisch (2006); Haines et al. (2002); Heinonen-Guzejev et al. (2007); Díaz Olariaga (2018); ICAO (2013); ICAO (2022); Karakoc et al., (2019); Licitra & Ascari, (2014); ACI (2022); ACI (2021); ACI (2020); ACI (2019).
Emissions reduction, air quality management, and energy efficiency.	Halpern & Graham (2018); Young & Wells (2019); Budd & Iverson (2017); Bamidele (2023); Karakoc et al., (2019); Čokorilo (2016); Monsalud et al., (2015); Postorino & Mantecchini (2014); ACA (2023); ACI (2022); ACI (2021); ACI (2020); ACI (2019).
Water management.	Guillamón (2010); Carvalho et al. (2013); Li et al., (2022); Young & Wells (2019); ACI (2022); ACI (2021); ACI (2020); ACI (2019).
Waste management.	Budd & Iverson (2017); Guillamón (2010); Kumar et al., (2016); Baxter (2022); ACI (2022); ACI (2021); ACI (2020); ACI (2019).
Sustainable design and construction.	Ferrulli (2016); Chang & Yeh (2016); Korba et al., (2022); ACI (2022); ACI (2021); ACI (2020); ACI (2019).
Management and monitoring of environmental processes (diverse topics/concepts).	Kumar et al. (2020); Budd & Iverson (2017); Dimitriou & Karagkouni (2022); Young & Wells (2019); Ferrulli (2016); ACI Europe (2015); Kilkis & Kilkis (2016); Dalkiran (2022); ACI Europe (2019); ACI Europe (2015); ACRP (2013); ACI (2022); ACI (2021); ACI (2020); ACI (2019).

Therefore, and in this vein, a green airport should be understood as an airport infrastructure whose management and operation are based on sustainability criteria, which, according to Airports Council International Europe (2015, 2019) and the National Academies of Sciences, Engineering, and Medicine (Haseman, 2013) implies that:

a. the organization has defined an environmental policy;
b. has an environmental management system following its environmental policy;
c. makes efficient use of available energy;
d. uses renewable energy sources in its facilities;
e. efficiently manages its solid waste and landfills;
f. makes rational use of water and other natural resources;
g. has procedures that minimize the impacts associated with operations;
h. has procedures to reduce greenhouse gas emissions and local pollutant emissions;
i. promotes good environmental practices and complies with local environmental legislation[1].

It can be seen, then, that these criteria focus on implementing technologies and technical methodologies that aim to reduce the negative environmental impacts of airports2. This vision is one of the prevailing environmental discourses in the industry for constructing a sustainability policy in aviation, emphasizing the ecological modernization of airports.

ENVIRONMENTAL IMPACTS GENERATED BY THE AIRPORT

The environmental quality in an airport's surroundings can be affected by multiple impacts associated with airport activity. Therefore, it is customary to segment them as follows, following what is proposed by Guillamón (2010), Young and Wells (2019), and Li et al. (2022):

a) Direct impacts are those from a direct consequence of the airport and its operation.
b) Indirect impacts are characterized by not being directly linked to the airport, although they are associated with its existence.
c) Induced impacts are those generated due to the airport's existence but not by the direct action of its installation or operation.

Based on this, an analysis is made that focuses on the environmental problems related to the airport and its operations.

NOISE

The noise generated by aircraft, whether from flyovers, during takeoff and landing, or when taxiing (runways, taxiways), is one of the most immediate and challenging environmental problems of the airport industry, as it is one of the factors that cause the immediate reaction of neighboring communities to the airport, on being a problem that affects the health and well-being of residents in their area of influence.

Epidemiological studies suggest that exposure to aircraft noise is related to specific adverse effects on the psychological, physiological, and cognitive performance of those affected, which include sleep disturbances and/or interruption (Fyhri & Aasvang, 2010), increased stress (Meister & Donatelle, 2000), hypertension (Babisch, 2006), reading difficulties for children and hearing loss (Haines et al., 2002).

Other studies claim that noise sensitivity may be a risk factor for people with cardiovascular problems (Heinonen-Guzejev et al., 2007). In short, limiting or reducing the number of people affected by noise is nowadays a key priority (Díaz Olariaga, 2018; Licitra & Ascari, 2014).

AIR QUALITY

Emissions of polluting gases such as CO_2, NO_x, and CO do not come exclusively from aircraft, either in flight or in their ground operations. The means of transport that facilitate access to the airport, the energy consumption (either gas or electricity), and the service vehicles that support airport operations, specifically in the area known as the 'airside,' are also significant sources of these pollutants. Together, these elements contribute to the degradation of air quality in the areas around the airport, as noted by Halpern and Graham (2018) and Young and Wells (2019).

1 Local environmental legislation is understood here as all the environmental criteria and/or requirements that, depending on the country, must be met so that an airport is not penalized in its operations or an expansion project or new airport is approved.

2 As an example or reference in a later subsection, figures on the positive impact on environmental indicators, results of the methodologies, and strategies implemented by airport managers are presented.

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Even though air quality regulations differ between countries, airport managers document and communicate the emissions produced, categorizing them into the following sources, according to Budd and Iverson (2017):

a. Direct emissions originating from resources that are under the ownership or management of the airport, including vehicles operating on the airside or airport buildings;
b. Indirect emissions mainly associated with the acquisition of electricity generated elsewhere for use in airport facilities;
c. Other indirect emissions derived from the airport's activities, ranging from aircraft operations to the diverse means of transport that access the airport.

The third group (c) emissions constitute the most significant proportion of airport emissions, as Bamidele et al. indicate. (2023). However, these are also the emissions where the airport operator usually exercises little or no control.

Two primary sources of poor air quality have caught the attention of airport operators: land access to the airport and transport vehicle service on the air side of the airport. Concerning the former, the cooperation of local authorities is vital to encourage public transport to and from the airport and to implement renewable energies in their public transport systems (Janić, 2018). On the other hand, regarding the second source of pollution, it should be noted that many airports are already using electrically powered service vehicles on the airside.

GREENHOUSE GAS EMISSIONS

The airport power plant, the (service) vehicle fleet, the maintenance of airport infrastructure, the apron support equipment, emergency power equipment, waste disposal systems, etc., constitute significant sources of greenhouse gas emissions. In this sense, the elements that predominate in generating these gases at an airport include the air conditioning equipment of buildings, interior lighting, and assistance services to the aircraft on the apron. On the other hand, although they represent a smaller proportion, beaconing, apron lighting, and air navigation assistance equipment also contribute to the total cost of an airport's energy bill (Karakoc et al., 2019).

SOIL AND GROUNDWATER AND SURFACE WATER POLLUTION

Water pollution can result from a direct or indirect discharge of substances into streams or water bodies, which causes alterations in the properties of water's natural ecosystems and chemistry. Surface waters are the most vulnerable to pollution, as pollutants can be washed from the paved surfaces of the airport (runways, taxiways, and apron) into nearby streams, rivers, wetlands, and lakes. Groundwater can also be affected when leaks or spills of industrial liquids infiltrate the soil (Guillamón, 2010; Santa et al., 2020).

WASTE GENERATION

Airports generate different types of hazardous and non-hazardous waste due to their varied operations (Budd & Iverson, 2017; Guillamón, 2010). These can be classified into:

a. Hazardous waste derived from maintenance facilities.
b. Organic and inorganic waste produced by airport concessionaires, such as shops.
c. Non-necessarily toxic inorganic waste generated by the airport administrative offices.
d. Items confiscated at security checks and in checked baggage.
e. Organic products, such as different types of food confiscated at customs controls.
f. Waste generated during aircraft cleaning operations.
g. Waste originating from construction and civil works at the airport.
h. Industrial waste.
i. Wastewater and stormwater that has been contaminated.

ENVIRONMENTAL MANAGEMENT STRATEGIES

In addition to providing obvious environmental benefits, effective strategies supported by public policies, programs, and measures should allow for better anticipation and rapid resolution of environmental problems without affecting economic performance or business opportunities (Budd & Iverson, 2017). In the specific case of airports, these strategies can be focused on improving environmental management, monitoring, and operational practices (Dimitriou & Karagkouni, 2022; Young & Wells, 2019).

NOISE POLLUTION CONTROL

Noise pollution is one of the primary sources of complaints and grievances by residents living near airports. To reduce noise emissions from primary operations, such as takeoffs and landings, airports worldwide have been gradually implementing the 'balanced approach' criteria promoted by the *International Civil Aviation Organization* (ICAO, 2014). This approach comprises four key elements:

1. Noise reduction at the source.
2. Operational procedures for noise attenuation.
3. Land use management and planning.
4. Introduction of operational restrictions.

For the first element, the aeronautical industry has been working for years on designing and constructing quieter engines, an area that airports have no competence or control over (International Civil Aviation Organization, 2022; Karakoc et al., 2019).

The third element is also beyond the competence and control of the airport, as the management of land use in the vicinity of the airport depends exclusively on the local authorities. However, the airport does have competence and control over the second and fourth elements. In particular, introducing operational restrictions, to the fourth element, is currently the most applied tactic in the largest airports in the world (Licitra & Ascari, 2014).

AIR QUALITY CONTROL

Since the harmful effects of the primary air pollutants produced by airport operations were recognized, governments and international organizations have developed regulations and programs to minimize their adverse impact on health and the environment. Therefore, monitoring programs must be designed with regard to the following conditions (Čokorilo, 2016):

a. It is always possible to know the contamination values reliably and immediately, complying with the standardized and accredited values.
b. That allows determining the atmospheric dispersion processes of pollutants using the correct location of the monitoring stations.
c. If the data are significant, the specific pollution crises can be controlled and their evolution analyzed.

Simultaneously, the airport can improve local air quality by applying different measures depending on the specific source of the pollutants (Greer et al., 2020; Karakoc et al., 2022).

CONTROL OF GREENHOUSE GAS EMISSIONS

To control polluting emissions, airports have begun to modernize power, heating, and cooling plants to improve efficiency while innovating by generating energy from renewable sources. Similarly, airport buildings are being designed (or redesigned) to be ‘smart’ and energy efficient, which puts them on par with specific international standards (Karakoc et al., 2019).

While some airports have already started working on ‘energy efficiency,’ this is not yet standard in airport infrastructure design. It is understood that energy efficiency is a set of intelligent measures applied to a specific environment that allows energy savings in any of its forms while maintaining the energy system’s quality and service levels of said environment without compromising the established objectives. Sustainable energy use necessarily implies improving energy efficiency, which leads to decreased greenhouse gas emissions (Monsalud et al., 2015). Thus, according to Postorino and Mantecchini (2014), energy efficiency in an airport infrastructure should a) guarantee the safety and operability of the airport, b) contribute to the transport of passengers and goods, and c) improve the energy efficiency of the processes that are part of its activity.

In this sense, airports increasingly opt for the Airport Carbon Accreditation (ACA, 2023) program certification, the only global carbon management certification program for airports institutionally supported by the Airports Council International (ACI). The ACA provides a single common framework and tool for active carbon management at airports with measurable results, covering the operational activities that contribute most to carbon emissions.

The *Airport Carbon Accreditation* evaluates and recognizes the efforts of airports to manage and reduce their carbon emissions through six levels of certification or accreditation, which are graphed in Figure 1: ‘mapping’ (carbon footprint measurement), ‘reduction’ (carbon footprint reduction management), ‘optimization’ (third-party participation in carbon footprint reduction), ‘neutrality’ (carbon neutrality for direct emissions through trade-offs), ‘transformation’ (transformation of airport operations and those of its trading partners to achieve absolute reductions of emissions), and ‘transition’ (counteracting residual emissions through reliable trade-offs) (ACA, 2023).

WATER QUALITY CONTROL

Airports consume significant amounts of water to provide essential services to passengers, employees, visitors, and other facilities, equipment, and infrastructure. Currently, water is no longer perceived as an unlimited resource, and the cost of its supply is increasing, so airports are managing water consumption to reduce costs and as part of their sustainable development strategy.

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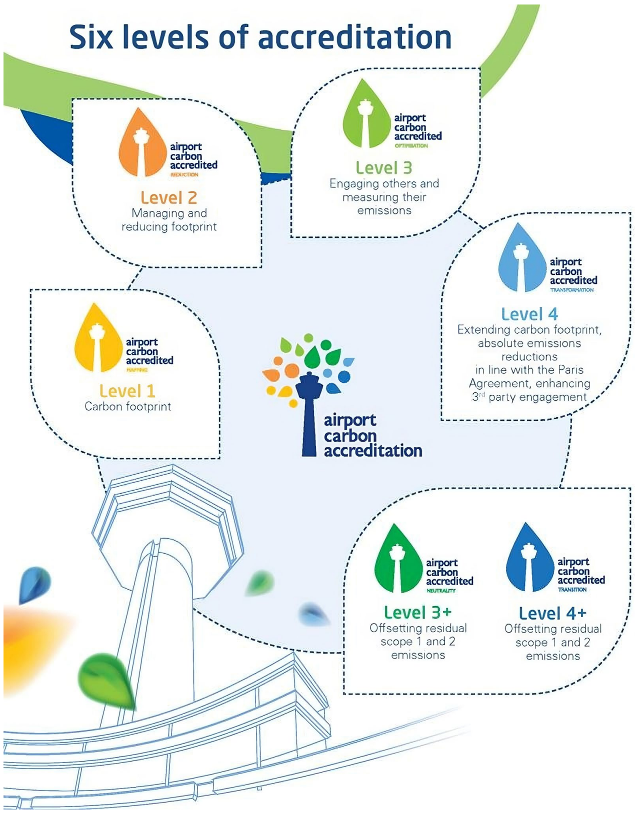

Figure 1: Carbon management accreditation levels for airports. Source: Airport Carbon Accreditation (https://www.airportcarbonaccreditation.org/)

In terms of resource management, there are two fundamental approaches to drinking water conservation: on the one hand, reducing its use and, on the other, replacing drinking water from the network with other sources, such as rainwater collection and reuse, wastewater treatment and cooling water recycling (Carvalho et al., 2013; Guillamón, 2010; Li et al., 2022; Young & Wells, 2019).

OPTIMAL WASTE MANAGEMENT

Baxter (2022) points out that the primary intention of airports regarding environmental practices is to reduce waste generation, which results in a positive image for the airport. In this sense, Guillamón (2010) shows that airports have been working at three hierarchical levels to manage generated waste efficiently. The first is to prevent waste generation to avoid unnecessary production. The second level is implementing reuse policies, and the third is establishing recycling strategies.

Waste management is a critical environmental problem that airports must face worldwide (Baxter et al., 2018). The solid and hazardous waste produced by airports can mainly be processed in three ways: recycling, incineration, and landfill disposal. Thanks to innovation, waste is increasingly being considered a resource to be optimized, thus minimizing its negative environmental impact.

The waste hierarchy approach focuses on its prevention, which is a crucial pillar in the green economy and contributes to improving efficiency in the use of resources and reducing the need for raw materials. This hierarchy starts with prevention and continues with reuse, recycling, recovery, and finally disposal (Kumar et al., 2016).

SUSTAINABLE DESIGN AND CONSTRUCTION

The design and construction of airport infrastructures are challenging for contemporary airport engineering due to the need to consider environmental concerns (Ferrulli, 2016). For this reason, airports should be developed so that environmental constraints do not affect operational capacity and future development. On the other hand, airport authorities can implement green building practices to make airport buildings more environmentally friendly (Chang & Yeh, 2016).

ENVIRONMENTAL PROCESS MANAGEMENT AND MONITORING

Public and political pressure and legislation tightening have led the airport industry to pay greater attention to environmental mitigation. From this, environmental management, monitoring, and operational processes have been deeply integrated into the business strategies of most airport operators.

Similarly, environmental management systems have been widely adopted to provide benchmarks to ensure coordinated responses to various environmental problems. That is why implementing reliable and replicable monitoring regimes is vital to environmental impact assessments and management systems (Kumar et al., 2020).

IMPACT OF ENVIRONMENTAL MANAGEMENT ON INDICATORS

During at least the last two decades, many of the world's airports have begun implementing actions and strategies to become environmentally sustainable infrastructures. As mentioned, airport managers must work in several operational areas, with medium and long-term plans that require significant capital investments to improve the different environmental indicators affected by airport activity. To illustrate the potential of how airport managers can positively impact environmental indicators with their actions and strategies, Table 2 presents statistics of recent experiences of several medium and large international airports that handle 20 to 40 million passengers annually in different regions of the world.

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Table 2: Impact of the airport's environmental strategies on the indicators. Reference figures in medium-large international airports (which handle between 20 and 40 million passengers/year) in the last four years. Source: Airports Council International, 2022; Airports Council International, 2021; Airports Council International, 2020; Airports Council International, 2019.

Indicator	Action / Strategy	Reduction / Saving
Emissions	Electric buses and service vehicles on the airside	91% reduction of emissions per year (342 T of CO_2/year; 202 Kg of NOx/year)
Emissions	Advanced air conditioning control system in the Passenger Terminal	Savings of 1.7 million kWh/year and 630 T of CO_2
Emissions	Use of LED lights in Passenger Terminal	32% reduction of CO_2 emissions/year
Emissions	Clean geothermal heating and cooling system (for Passenger terminal)	83% reduction of CO_2 emissions/year
Emissions	Use of LED lights on the runways/taxiways	Reduction of CO_2 emissions (for two runways): 712 T of CO_2/year.
Emissions	Solar-powered ground support equipment for aircraft	Annual reduction of 102,209 liters of diesel and emissions: NOx (1,672 kg); CO (965 kg); PM (190 kg).
Electricity	Implementation of energy efficiency program (for the entire airport)	26% reduction in electricity consumption per year
Air quality	Installation of continuous monitoring stations for ambient air quality	12.5% annual reduction of emissions (including gaseous and particulate matter)
Air quality	Implementation of an air quality management system	Reduction of concentrations (per year): SO_2 49%, NOx 6.7%, NO_2 11.7%, PM10 27.6%, PM2.5 26.3%
Air quality	Air pollutant reduction plan	Annual reduction: 10.1 T of TSP, 1.7 T of PM10, 1.2 T of PM2.5, 59.9 T of NOx, 36.1 T of SOx, 49.9 T of CO, and 12.5 T of non-methane hydrocarbons.
Aviation fuel	Taxiing of aircraft on the ground with a single engine	Saving 4,382 kl of fuel/year
Water	Implementation of a water management system	30.92% efficiency in the use of water. Internal resources such as treated wastewater and surface water cover 50% of the airport's water demand.
Water	Rainwater recycling system	Reduction of 50% of the total network water used inside the passenger terminal.
Water	Dry cleaning of aircraft	90% reduction of water use.
Water	Installation of high-efficiency cooling towers	Reduction of 72,154 tons/year of water consumption in the passenger terminal.
Waste	Waste minimization system through composting and organic waste treatment	Annual reduction of 238 T CO_2, avoiding the dumping of 353 MT/year of waste from food in landfills, generating 276 MT of fertilizers for landscaping and horticulture.
Waste	Waste management and recycling system	57% overall reduction in waste going to landfills.
Waste	Waste separation and recycling system	30.8% of general waste is recycled. 93.7% of the waste disposed of is used as a waste-derived fuel for cement production.

CONCLUSIONS

The extensive thematic review of the 'green airport' concept shows some convergence among academics regarding the structure or development framework on which airport management should be based to achieve environmental sustainability. The course of action proposed by most studies and research begins by identifying the environmental aspects negatively affected by airport activity. Then, the source of the environmental impacts is identified, and finally, actions, strategies, and methods are formulated to mitigate or offset the generated impacts.

A common denominator of the literature analyzed is the recommendation that an airport should be environmentally sustainable or 'green,' and airport managers should implement ecological practices in their core competencies due to strict environmental standards and strict regulations (required in their respective countries). The growing competition has drawn the attention of airport authorities worldwide to adopt green practices in their organizational and operational activities.

In short, airports may be limited by environmental issues that restrict current operations and limit future potential growth. To maximize growth opportunities, it is necessary to consider all the factors involved in the construction and operation of an airport to avoid environmental impacts that impact sustainability strategies. The life cycle and long-term planning of airport infrastructures require a systemic approach to meet the need for change through a better definition of management processes and compliance with environmental sustainability requirements.

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EXPLORING SUSTAINABLE APPROACHES AT DUBAI EXPO 2020: A BLEND OF BIOPHILIC AND BIOMIMICRY DESIGNS

EXPLORACIÓN DE ENFOQUES SUSTENTABLES EN LA EXPO DE DUBÁI DE 2020: UNA MEZCLA DE DISEÑOS BIOFÍLICOS Y BIOMÍMESIS

EXPLORANDO ABORDAGENS SUSTENTÁVEIS NA DUBAI EXPO 2020: UMA MISTURA DE DESIGNS BIOFÍLICOS E BIOMIMÉTICOS

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ABSTRACT

Dubai Expo 2020 provides an international platform for advancing innovation through meticulously curated exhibits with themes such as sustainability and cultural exchange displayed in pavilions dedicated to individual countries. This research study uses biophilic or biomimetic design strategies to assess the sustainability practices employed in a group of pavilions at the Dubai Expo 2020 that employ biophilic and/or biomimetic design strategies. Biophilic philosophy emphasizes nature-based concepts to foster positive relationships between humans and living organisms, whereas biomimicry imitates natural processes/systems for building practices. Incorporating biophilic and/or biomimetic techniques into pavilion design provides visitors with a one-of-a-kind experience while displaying explicit sustainability principles that go beyond the event's existing architectural framework guidelines. The research evaluation process includes architectural structure designs, materials used during production/creation periods, energy efficiency measurements implemented, and sustainable water management plans based on natural ecological systems. It will also evaluate the adherence of each pavilion chosen to genuine sustainability values by analyzing the incorporation of nature-based concepts into its overall design for potential future reference applications. These techniques have significant potential to improve human health, reduce environmental impact, and encourage global resiliency when implemented beyond Dubai Expo 2020. In conclusion, the research aims to inspire sustainable designs well beyond the Dubai Expo 2020 by demonstrating how biophilic or biomimetic practices are crucial facilitators in constructing spaces that maximize human welfare without endangering the environment. It is also a foundational resource for architects and urban planners committed to advancing sustainable architectural practices through future development projects prioritizing human welfare and environmental protection.

Palabras clave
Expo Dubai 2020, sustainability, biophilic, biomimicry, nature-based

RESUMEN

La Expo de Dubái 2020 es una plataforma internacional para el avance de la innovación a través de exposiciones meticulosamente seleccionadas, con temas como la sostenibilidad y el intercambio cultural expuestos en pabellones dedicados a países individuales. Esta investigación usa estrategias de diseño biofílico o biomimético para evaluar las prácticas de sustentabilidad usadas en un grupo de pabellones en la Expo de Dubái de 2020, que usan estrategias de diseño biofílico y/o biomimético. La filosofía biofílica hace hincapié en conceptos basados en la naturaleza, con el objetivo de fomentar relaciones positivas entre los seres humanos y los organismos vivos, mientras que la biomímesis imita los procesos/sistemas naturales para las prácticas de construcción. La incorporación de técnicas biofílicas y/o biomiméticas en el diseño de los pabellones proporciona a los visitantes una experiencia única, al tiempo que muestra principios de sostenibilidad explícitos que van más allá de las directrices del marco arquitectónico del evento. El proceso de evaluación de la investigación incluye diseños de estructuras arquitectónicas, los materiales utilizados durante los periodos de producción/creación, las medidas de eficiencia energética aplicadas y los planes de gestión sostenible del agua basados en sistemas ecológicos naturales. También se evaluará la adhesión de cada pabellón seleccionado a auténticos valores de sostenibilidad analizando la incorporación de conceptos basados en la naturaleza en su diseño general para posibles aplicaciones futuras de referencia. Estas técnicas tienen un potencial significativo para mejorar la salud humana, reducir el impacto ambiental y fomentar la resiliencia global cuando se lleven más allá de la Expo de Dubái de 2020. En conclusión, la investigación apunta a inspirar diseños sostenibles mucho más allá de la Expo de Dubái de 2020, al demostrar cómo las prácticas biofílicas o biomiméticas sirven de facilitadores clave en la construcción de espacios que maximizan el bienestar humano, sin poner en peligro al medio ambiente. También sirve como recurso fundamental para arquitectos y urbanistas comprometidos con el avance de las prácticas arquitectónicas sostenibles a través de futuros proyectos de desarrollo, que den prioridad tanto al bienestar humano como a la protección del medio ambiente.

Keywords
Expo de Dubái 2020, sustentabilidad, biofílica, biomímesis, basada en la naturaleza

RESUMO

A Dubai Expo 2020 oferece uma plataforma internacional para o avanço da inovação por meio de exposições meticulosamente selecionadas com temas como sustentabilidade e intercâmbio cultural exibidos em pavilhões dedicados a países individuais. Este estudo de pesquisa utiliza estratégias de design biofílico ou biomimético para avaliar as práticas de sustentabilidade adotadas em um grupo de pavilhões da Dubai Expo 2020 que empregam estratégias de design biofílico e/ou biomimético.A filosofia biofílica enfatiza conceitos baseados na natureza para promover relações positivas entre humanos e organismos vivos, ao passo que a biomimética imita processos/sistemas naturais para práticas de construção. A incorporação de técnicas biofílicas e/ou biomiméticas no projeto do pavilhão proporciona aos visitantes uma experiência única, ao mesmo tempo em que exibe princípios explícitos de sustentabilidade que vão além das diretrizes de estrutura arquitetônica propostas para o evento. O processo de avaliação da pesquisa inclui projetos de estruturas arquitetônicas, materiais utilizados durante os períodos de produção/criação, medidas de eficiência energética implementadas e planos de gerenciamento sustentável da água com base em sistemas ecológicos naturais. Ele também avaliará a adesão de cada pavilhão escolhido aos valores genuínos de sustentabilidade, analisando a incorporação de conceitos baseados na natureza em seu projeto geral para possíveis aplicações futuras de referência. Essas técnicas possuem um potencial significativo para melhorar a saúde humana, reduzir o impacto ambiental e incentivar a resiliência global se forem implementadas após a Dubai Expo 2020. Por fim, a pesquisa tem como objetivo inspirar projetos sustentáveis muito além da Dubai Expo 2020, demonstrando como as práticas biofílicas ou biomiméticas são facilitadoras cruciais na construção de espaços que maximizam o bem-estar humano sem colocar em risco o meio ambiente. É também um recurso fundamental para arquitetos e planejadores urbanos comprometidos com o avanço das práticas arquitetônicas sustentáveis por meio de futuros projetos de desenvolvimento que priorizem o bem-estar humano e a proteção ambiental.

Palavras-chave:
Expo Dubai 2020, sustentabilidade, biofílico, biomimética, baseado na natureza.

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INTRODUCTION

Emulating life's creativity is crucial for human survival and a sustainable future. Nature serves as a source of design inspiration for the built world, as it understands sustainable construction. Sustainability is a significant factor in design, and understanding the value of nature and its influence on design is essential. Nature's natural cycles, such as providing food for insects and fruits for variety, have been challenging for humans to complete since humanity's inception (Green, K, 2005; Karabetça, A.R., 2015).

Nature is critical to reaching the worldwide goal of net zero emissions by 2050. However, according to United Nations Secretary-General Antonio Guterres, nature needs assistance. We can escape climate catastrophe and restore our world by defeating the COVID-19 pandemic (Aboulnaga & Helmy, 2022). Biophilia, bioengineering, bionics, and biomimicry are biological terms that describe the laws of nature that have governed 30 million species for 3.85 billion years (Isle & Leitch, 2023). Bio-concepts, such as biophilia and biomimicry, are used to integrate nature into human activities, focusing on Janine Benyus' principles for sustainability. This study explores these concepts in architecture.

BIOPHILIC DESIGN

The creation of biophilic design has taken many steps in history. As shown in Figure 1, it has involved considering guidelines in the design phase, incorporating natural characteristics into built environments, and representing shapes like botanical, animal, and shell motifs through arches, vaults, and domes, varying sensory experiences through time, change, transitions, and complementary contrasts (Terrapin Bright Green, 2014). This type of design evokes historical, cultural, geographic, spiritual, and ecological significance, transforming humans and creating nature-like environments (Biancardi & Cascini, 2023; Al-Rhodesly, 2019). Biophilic Design focuses on reconnecting with nature, transforming human awareness, and fostering a new ethic of duty for caring for the world (Van der Ryn & Cowan, 2013; Thampanichwat et al., 2013). Mass and volume are linked to biophilic design, with material, object, light, landscape, and viewpoint referencing natural elements, without examining color or sound details.

BIOMIMICRY

From the Greek words bios-life and *mimesis*-mimic, imitate, biomimicry translates to "the imitation of life." Engineering, product design, and architecture all use biomimicry, which takes inspiration from nature's mechanisms and applies them to the shortcomings humans face (Thampanichwat et al., 2013; Taylor Buck, 2017). Biomimicry in design can promote climate action, build green, sustainable cities, achieve sustainable development, and comply with the United Nation's SDGs. Incorporating natural elements into a design can inspire sustainability and protect ecosystems in the face of climate change and COVID-19 while combining architectural features with nature and technology can overcome city resilience challenges (Aboulnaga & Helmy, 2022).

Designers are increasingly aware of the natural opportunities to enhance human and system functionality. This has increased interest in biomimicry for built environments and sustainability (Oguntona & Aigbavboa, 2023; Jamei & Vrcelj, 2021). Architecture that uses biomimicry takes cues from the methods, tools, and ideas employed by other organisms to suit their needs and secure their existence on Earth. J. Benyus proposes two key methods for using biomimicry (Jamei & Vrcelj, 2021; Aamer et al., 2020). Biology-to-design aims to solve design challenges by identifying basic functions and analyzing natural principles. This approach enables advanced, sustainable buildings with aesthetical, physical, and mechanical aspects. Designers can create this technique by collaborating with nature, existing practices, or experimental design-science (Fahmy, 2018). The parallels between nature and architecture in this context have motivated numerous researchers to use biological systems to manage environmental variables (Varshabi, Arslan Selçuk, & Mutlu Avinç, 2022; Perricone et al., 2021). As a result, biomimicry-based design has arisen as a transdisciplinary, groundbreaking architectural movement (Faragalla & Asadi, 2022).

Sustainable pavilions at expos typically focus on environmentally friendly practices, energy efficiency, and the use of renewable resources. These pavilions often incorporate green building technologies, sustainable materials, and innovative designs that minimize their environmental impact. These pavilions may showcase advancements in renewable energy, waste reduction, water conservation, and sustainable living practices.

Features of sustainable pavilions are achieved within biophilic and biomimicry design frameworks and may include:

- Solar panels for energy generation.
- Rainwater harvesting systems.
- Sustainable and recyclable construction materials.
- Smart technologies for energy management.

OBJECTIVES AND METHODS

The objective is to inspect and analyze biophilic and biomimicry features applied in Dubai expo's pavilions

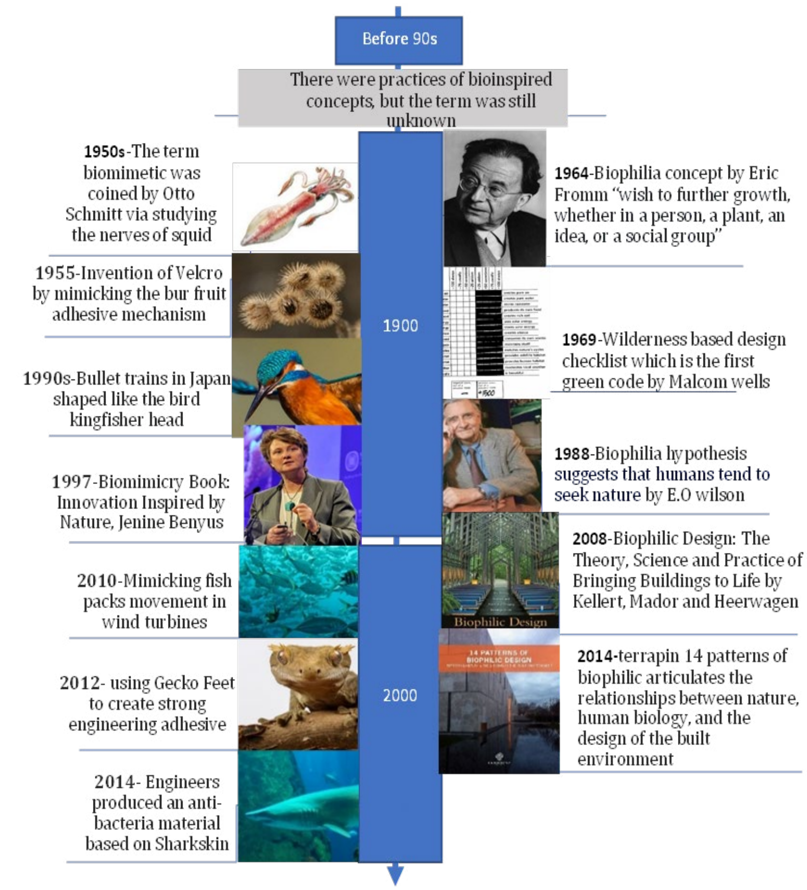

Figure 1. Summarized history of Biophilic and Biomimicry design. Source: Schreiner, (2018); University of Minnesota, (2023); Zare et al., (2021).

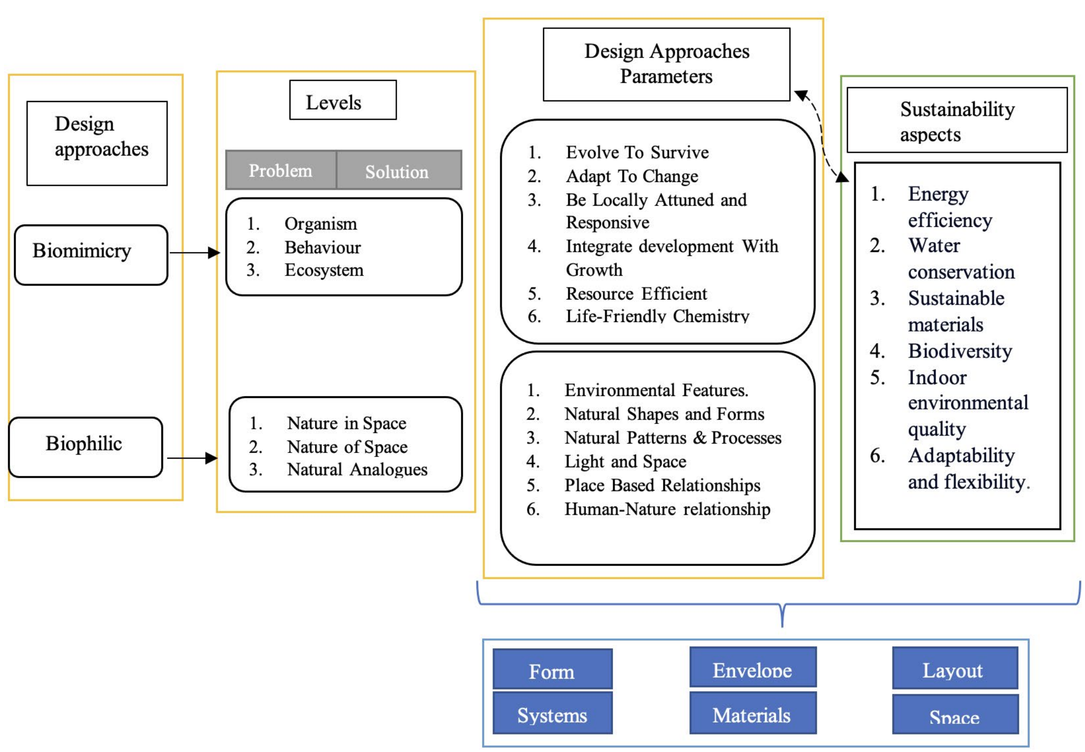

Figure 2. Flow chart of the study analysis framework. Source: The authors.

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through their architecture and relationship with sustainability approaches.

1. Evaluate the integration of biophilic and biomimetic concepts in pavilion architecture.
2. Examine how these strategies enhance explicit sustainability principles.
3. Analyze architectural elements, materials, and their compatibility with these strategies.
4. Measure reduced environmental impact and potential energy efficiency gains.
5. Validate the long-term applicability of these techniques beyond the Expo.

The methodology evaluates the biophilic and biomimicry features in terms of sustainability:

1. Establishing a biophilic and biomimicry identification and categorization guide
2. Referencing biophilic design to green designs and biomimicry as science to learn strategies from nature.
3. Identifying sustainability criteria and goals
4. Analyzing each biophilic and biomimicry feature in terms of sustainable design principles / biophilic design principles

ANALYSIS FRAMEWORK

The identification and categorization guide for the five pavilions at the Dubai Expo focuses on biomimicry and biophilia concepts. It involves collecting and recognizing building elements, such as ventilation systems and architectural design, and classifying them using a checklist (Figure 2). Successful elements are considered under the study concepts, and the number of parameters added measures the strength of the concept's implementation.

There are some characteristics shown in Table 1 that aid in recognizing whether a building element responds to a particular parameter. Realistically, the building elements are identified from data that can be analyzed in different ways depending on the purpose of the

Table 1. Biomimicry and Biophilic design characteristics. Source: Kellert, 2008

Biomimicry parameter	Characteristics	Biophilic parameter	Characteristics
Evolve to survive	Replicate strategies Embody information Redo successful approaches Create new options	Environmental Features.	Air, Water, Plants Animals, Materials
Adapt to change	Respond to dynamic contexts Incorporate diversity Self-renewal Embody resilience Meet a functional need	Natural Shapes and Forms	Botanical Motifs Shells and spirals Curves and arches Fluid forms Abstraction of nature
Be locally attuned and responsive	Use available resources Integrate within the surrounding	Natural Patterns and Processes	Sensory richness Area of emphasis Patterned wholes Bounded spaces Linked series and chains
Integrate development with growth	Self-organize Start from simple to complex. Allow interactions	Light and Space	Composition Communication Preference Engagement Pragmatics Daylight Filtered light Reflected light
Resource efficient	Recycle all materials Fit form to function Multi-functional design One solution for multi-needs Low energy Processes	Place-based Relationships	Geographic connection Historic connection Ecological connection Cultural connection
Life-Friendly Chemistry	Use water as solvent. Small subset of elements. Support life processes.	Human-Nature relationship	Prospect/refuge Order/complexity Curiosity/enticement Attraction/attachment Exploration/discovery

analysis. Nevertheless, the characteristics are examples of what a biophilic and/or biomimetic element can be like, but not necessarily all that it can be. Understanding the parameters as fundamental for making judgments is key to the identification process; the guide is just there to guide, not to determine facts.

DUBAI EXPO 2020 PAVILIONS ANALYSIS

This study will focus on five pavilions of Belgium, Netherlands, Singapore, Sustainability, and UAE, spread all over the Dubai expo area. It is important to point out that all these pavilions are high-tech structures. They represent countries with high per capita income and vast resources to support them. Each pavilion will be introduced in general and analyzed by element; each building element (form, materials, layout, space, systems, and envelope) that possesses biophilic or biomimicry parameters will be represented here; the parameters are coded in reference to Table 2. These parameters define a vital part of the analysis framework (Figure 2); once the building element is recognized, the author can relate it to biophilic or biomimicry concepts (Kellert, 2008).

Table 2. Reference codes for biophilic and biomimicry parameters. Source: The authors.

Biophilic design	Code
Environmental Features.	P1
Natural Shapes and Forms	P2
Natural Patterns and Processes	P3
Light and Space	P4
Place-Based Relationships	P5
Human-Nature relationship	P6
Biomimicry	**Code**
Evolve to Survive	M1
Adapt to Change	M2
Be Locally Attuned and Responsive	M3
Integrate development with Growth	M4
Resource Efficient	M5
Life-Friendly Chemistry	M6

BELGIUM PAVILION

The Belgium Pavilion information is shown in Table 3. It was inspired by the notion of a "Green Arch" and forms a massive four-story rectangular structure wrapped in luxuriant vegetation. It comprises 500m² of exhibitions offering a glimpse into the future of Belgium's mobility technologies and innovations. A brasserie and takeaway kiosk for your fix of Belgium specialties in a luxurious yet cozy setting. A rooftop terrace with a lounge area for you to enjoy the sunset and the view. Almost 100 vertical strips of blonde wood line the pavilion's longest façades, rising skyward to resemble the ribs of a vast ship.

Table 3. Belgium Pavilion information. Source: Expo, 2020; Expo, 2021.

Architect	Assar / Vincent Callebaut
Theme	Diversity in harmony
Area	3,500 m²
Location	Mobility District

SOLAR CANOPY

The slender bridge-building shown in Figure 3 is a dynamic monolith dedicated to renewable energies, covered with a large photovoltaic and thermal solar canopy. This building element uses renewable natural resources such as sunlight to produce electricity and domestic hot water for the pavilion's self-consumption. Easing the pressure of limited natural resources and using what is abundant in the surroundings is one of the most natural behaviors of decomposers, using the dead tissues available everywhere in nature as a food source. (M5)

Figure 3. (A) Belgium pavilion's perspective and (B) roof plan indicating solar canopy. Source: Assar, 2020; Dey, 2021.

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THE PARABOLOID

The paraboloid shown in Figure 4 is built with more than 5.5 linear kilometers of spruce louvers, generating a giant wooden Mashrabiya. It is considered a significant cultural connection to the United Arab Emirates as part of heritage building design elements. (P5) The Mashrabiya, built in CLT, features a 180-degree rotating element for solar protection, energy efficiency, and natural ventilation. This contributes to (P1) because it is the integration of natural materials but highly contradicts (M3). The wood used in the building is not native and is likely imported, potentially reducing energy savings. The wrapping technique creates mystery and surprise in the building's shape and form. (P6) The element significantly impacts the building layout, emphasizing the main axis and creating a fluid shape, connecting urban surroundings and outdoor spaces (P1) (P5). The surface exposure to the outside is increased thanks to the curvature shape, allowing more daylight into the building, contributing to saving energy and better indoor environment quality (M5) (P6).

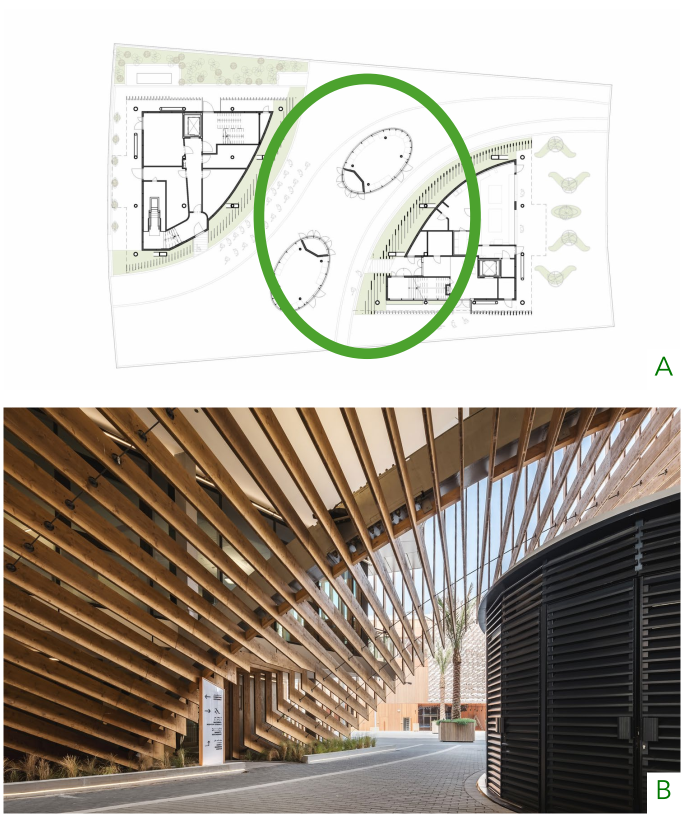

Figure 4. (A) Belguim pavilion's paraboloid indications on the ground floor and (B) a close-up with spruce louvers representing the Mashrabiya concept . Source: Assar, 2020; ArchDaily, 2021.

GREEN FAÇADE

The green arch features balconies and a rooftop with over 2,500 plants, shrubs, and trees. Drip-watered façades refresh outdoor terraces, promoting sustainable water delivery and resource preservation. Greenery aligned on different levels helps the building's cooling and energy savings (Figure 5) (M5). The approach involves using living organisms to solve problems, connecting the building's natural identity and form to nature, and enhancing its performance (P1).

Figure 5. (A) Belgium pavilion's green façade and (B) its indications on the plan. Source: Assar, 2020.

THE ESCALATOR

The futuristic escalator shown and indicated in Figure 6, designed as a space-time tunnel, propels visitors toward the 2050 Odyssey. This area induces sensory enrichment due to its interior design, which is unique from the rest of the building (P3). Making this design for a multiple-level system creates an experience involving mystery in the discovery at the end of the ride, primarily because this is an event-based building that is not regularly found in similar residential or commercial buildings (P6).

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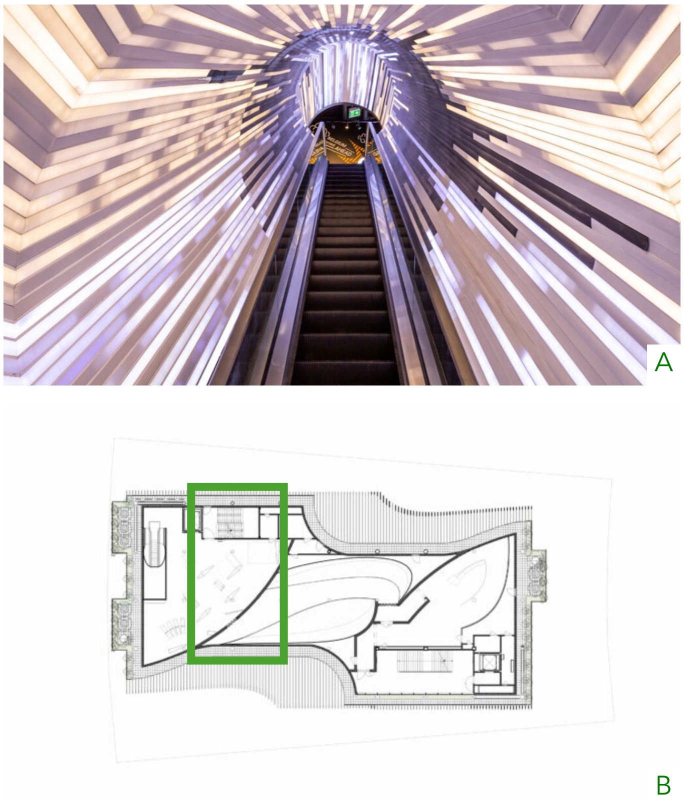

Figure 6. (A) Belguim pavilion space-time tunnel escalator and (B) its location on the plan. Source: Assar, 2020; ArchDaily, 2021.

NETHERLANDS' PAVILION

As the Netherlands' contribution to Expo 2020 Dubai, V8 (Table 4) Architects designed a pavilion with its own contained water, electricity, and food system, as well as a leave-no-trace mentality. The Dutch Biotope pavilion includes, in addition to the main exhibition space, an auditorium, VIP lounge, restaurant, store, and back offices on a total floor area of 3,727 square meters.

Table 4. Netherlands Pavilion information. Source: The National UAE, (2020).

Architect	V8 Architects
Theme	Sustainable solutions through out-of-the-box creativity
Area	3,727 m²
Location	Sustainability District

Biotope

Inside the pavilion, a large cone is the main element of the exhibit- a vertical farm covered in edible plants on the outside and mushrooms on the inside, as shown in Figure 7. Providing indoor natural elements that are also useful is a core in integrating development with growth (P5) (P1) and creating a solid ecological connection where the element is positioned and designed as a core part of the pavilion (M4). The chimney-like structure regulates temperature and moisture, harvesting water from air humidity for plant irrigation. Powering renewable energy from lightweight, transparent solar cells, the pavilion uses the sun's abundant sun and scarce water to feed 9,300 plants (M3). The result of creating such a significant natural element is the ability to minimize active system usage and energy use by relying on the natural process to regulate temperature (M5). The condensation process leaves high levels of CO_2, making the cone the ideal place to grow other kinds of food. The space is humid, dark, and cold; these are the perfect conditions for edible oyster mushrooms. You can smell them here as they grow inside the cone, creating a sensory-rich experience (P3).

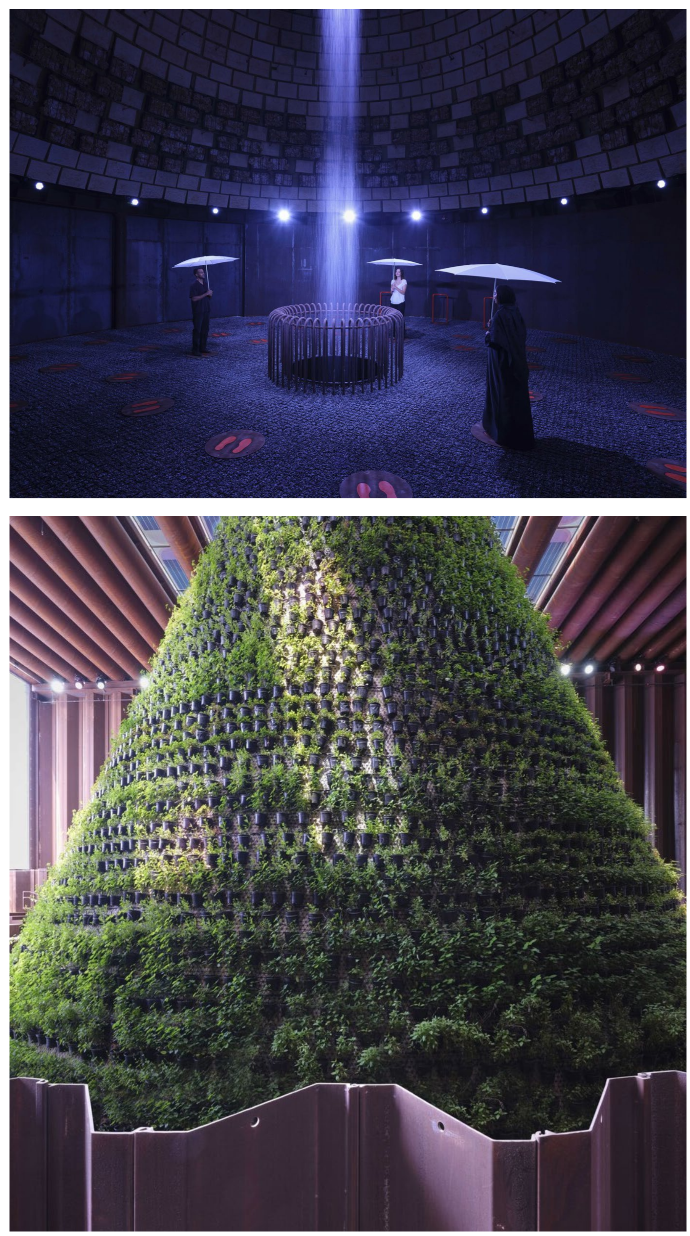

Figure 7. Netherlands Pavilion Biotope exhibiting vertical farm as a core. Source: Aouf, 2020.

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Entrance

Visitors descend into the pavilion on a ramp, as shown in Figure 7, and start experiencing the shift in temperature, creating a sense of exploration and discovery right at the beginning of the experience. The contrast of order and complexity reinforces the machine metaphor in the control room that leads inside the central cone, where the pavilion's technical innovations can be projected onto white umbrellas (P6).

Materials

The Netherlands Pavilion uses reclaimed iron, biopolymers, and bio-mass tiles for an eco-friendly exterior, promoting circular economy principles (M5) (M6). V8 Architects built the pavilion primarily from steel hired from locally based companies. Sand excavated from the site is used for filling the double sheet piling and as a temporary insulation material and will be used to fill the plot back in again after the Expo (M3). The walls shown in Figure 8 are made from steel sheet piling, and the roof is made from steel tubes, while concrete was avoided in the pavilion foundations to avoid harsh chemicals (M6). Amsterdam-based Buro Belén's biodegradable canopy and biopolymer maize curtain in the space enhance environmental connection and human-made construction elements (P1).

Figure 8. (A) Netherlands Pavilion 3D section showing materials, levels, and movement axis and (B) entrance gateway with a horizontal projection and leveling. Source: Aouf, 2021; The National UAE, 2020.

SINGAPORE PAVILION

The Singapore Pavilion at Expo 2020 Dubai exemplifies the city's desire for a sustainable future that integrates architecture, nature, technology, and culture (Table 5). The pavilion was developed by WOHA Architects and landscape design firm Salad Dressing to present a sample of Singapore's urban environment that exemplifies the city-state's City in Nature goal. Through the marriage of technology and nature, the multi-layered green space generates a self-sufficient ecosystem that highlights notions of sustainability and resilience.

Table 5. Singapore Pavilion information. Source: Expo 2020 – Singapore Pavilion, 2023.

Architect	WOHA
Theme	Nature. Nurture. Future.
Area	1,500 m²
Location	Sustainability District

The ground gardens

Singapore's multi-layered green space (Figure 9) showcases sustainability and resilience by integrating technology and nature. With over 170 plant species,

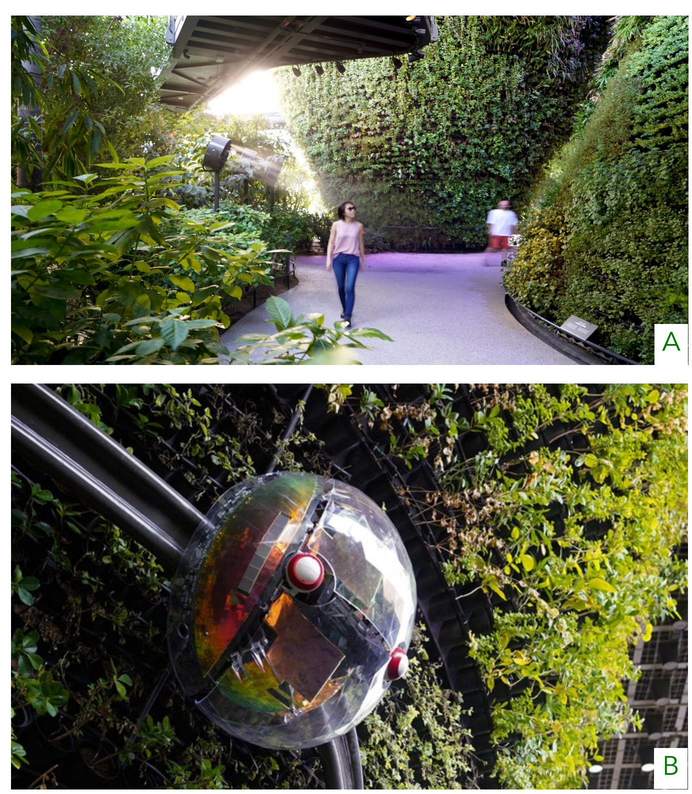

Figure 9. Singapore pavilion ground floor vertical garden and (B) climbing robots that act as a maintenance system. Source: Transsolar Klima Engineering, 2021.

visitors can experience tropical rainforests, mangrove areas, and forest streams, creating a rich bio environment (M4) (P3) (P1) (P6). Housing 80,000 plants from more than 170 plant varieties and an integrated system of greenery, energy, and water management within an efficiently designed 1,500-square-meter site is creating a new self-sufficient environment that mimics the sufficiency of nature as a system (M1).

Oceania Robotics developed three prototype climbing robots for vertical and skyrise gardens, utilizing communication systems reminiscent of living organisms to maintain greenery and monitor plant health (M4).

Thematic cones

The pavilion's biophilic design and architecture showcase nature as an urban solution, surrounded by 3 modular cones, vertical greenery, and a hanging garden. It features tropical trees, shrubs, orchids, and ethnobotanical plants. Innovative solutions like dry misting and solar pipes enable tropical plants to thrive, creating a sensory heaven (P1) (M4). The shape of the cone can be more thoughtful because nature is messy and not perfectly curved and geometrical (P2).

Experience an experiential journey through the Pavilion, featuring Ground Garden, Garden Cones, and Hanging Garden, showcasing Singapore's natural heritage, innovative urban solutions, and orchid species (P3).

Singapore pavilion offers comfortable, enjoyable walks with shading, vegetation cooling, and fine mist fans, saving resources and the cooling load in the desert (M5).

Sky market

Although the sky market in Figure 10A is isolated from the very dense greenery on the first two floors, it represents a great element of prospect, mystery, and discovery. On the other hand, the exterior in Figure 10 B clearly defines it as an endpoint for the nature journey by creating a completely opposite environment with plain walls, clean edges, and a central destination (P6).


A

B

Figure 10. (A) Singapore pavilion's exotic interior sky market and (B) its emphasis on the exterior. Source: form Transsolar Klima Engineering, 2021.

Solar canopy

The pavilion, powered by 517 solar panels, provides 161 MWh of power during the expo. It is self-sustaining in the harsh desert environment, using local resources and irrigation for the extensive greenery. The pavilion's design mimics nature's power, reducing the ambient temperature by 6-10°C (M5) (M3).

SUSTAINABILITY PAVILION

Grimshaw's (Table 6) pavilion is one of three flagship structures at Expo 2020 Dubai, which opened earlier this month, a year later than planned due to the pandemic. It contains 6,000 square meters of exhibition space and sits at the heart of the Expo's Sustainability District. It promises to show visitors "how we can change our everyday choices to reduce our carbon footprint and environmental impact."

Table 6. Sustainability Pavilion information. Source: Expo 2020 - Terra 2023.

Architect	Grimshaw Architects
Theme	Nature. Nurture. Future.
Area	1,500 m²
Location	Sustainability District

Energy and water system

The pavilion's design combines natural processes like photosynthesis, optimizing sunlight, and humidity harvesting, with a 130-meter roof, photovoltaic panels, and 18 "Energy Trees" for shade (M1). The pavilion's water management system uses condensation, filtered and disinfected, mixed with desalinated water, and generates power through rooftop photovoltaic panels. It

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generates clean water through wastewater, condensation, and brackish surface water—the combined usage of many sustainable resources achieves many of the region's sustainable goals (M5).

Materials

Sustainability Pavilion at Expo 2020 Dubai for having an embodied carbon footprint of almost 18,000 tons – a figure that is double the recommended level for a building of its size. Its spectacular steel canopy, shown in Figure 11, is responsible for significant, unnecessary, and harmful emissions that contribute to global warming and pollute nature (M6).

Figure 11. Sustainability pavilion exterior canopy made of steel and (B) photovoltaic trees that are nature-based in form and function. Source: Fairs, 2021; Prisco, 2021.

Form

The funnel shape shown in Figure 12 stimulates natural ventilation and brings daylight inside the pavilion. The curvature shape is a biophilic pattern, and its contribution to ventilation helps minimize cooling loads and save energy. Daylight acts as a natural element inside the pavilion and contributes to energy savings by reducing the need for artificial lighting (M5) (M4) (P2).

UAE PAVILION

The design of the UAE Pavilion evokes a falcon in flight, referencing the Emirates' traditional art of falconry. The main building resembles a titanic oval, with a grand, four-story entrance set into the tip. More than 25 feather-like panels are arranged at the dome of the pavilion, each curving down toward the structure's entrance (Table 7).

Table 7. UAE Pavilion information. Source: Expo 2022 – UAE Pavilion, 2023.

Architect	Santiago Calatrava
Theme	Introducing the UAE's rich culture and bright future
Area	15,000 m2
Location	Opportunity District

Roof design

The four-story pavilion was informed "by a falcon in flight" and is topped by a series of "wings," creating a natural shape and form for the entire building. To bring the pavilion's central theme of "falcon in flight" to life, the roof is designed in the shape of wings that portrays the flow of movement (P2). The sloped geometry of the roof and the floating wings create visual and outward connections that welcome visitors approaching the UAE pavilion from all directions, enhancing its accessibility (P5).

There are 28 wings made of carbon fiber and covered in PV panels, as shown in Figure 12. Hydraulic actuators fuel the wings' movement (M5). The entire roof can be opened in three minutes by spreading the wings, which gives the ability to adapt to change and create new options (M1) (M2). The structure protects panels from rain and sandstorms, while local sourcing and cold-forming processes minimize environmental impacts, conserving resources and enhancing local employment opportunities (M3) (M5).

Figure 12. UAE pavilion wing-like form. Source: Ravenscroft, 2021.

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Spherical Center

At the center of the 15,000-square-meter pavilion is a sphere-shaped void, as shown in Figure 13, that serves as an auditorium. It is surrounded by a multi-level gathering space, with a circular skylight incorporating the Expo 2020 logo. (P2) The platform, which supports the seating, can move and transport the audience between different floors, which creates a sense of dynamic discovery while meeting functional needs (M2) (P6). The Oculus skylight is designed like the Expo 2020 logo and is located at 27.8 meters. It provides daylight inside the pavilion space, reducing the need for artificial lighting by using a sustainable light source (P4).

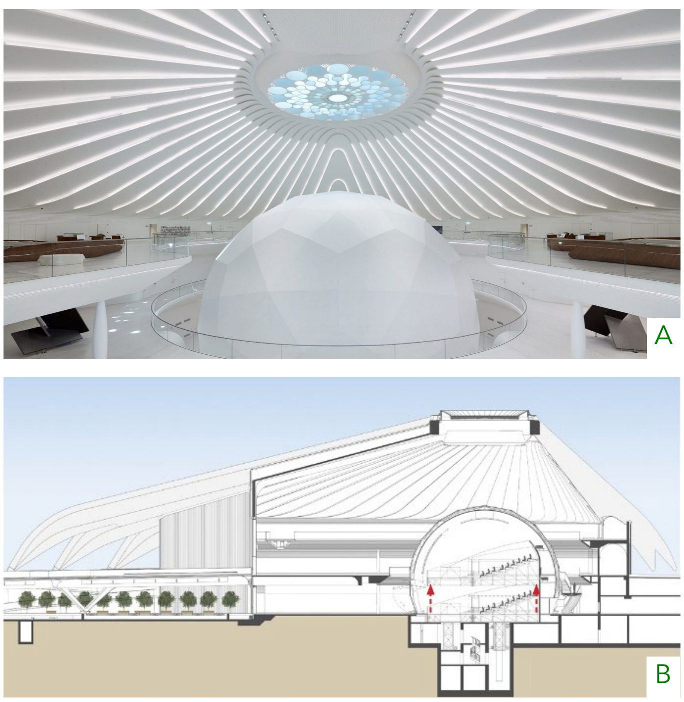

Figure 13. (A) UAE pavilion spherical core and (B) its section. Source: Ravenscroft, 2021.

Landscape

Moreover, the surrounding landscape shown in Figure 13 contains 80 trees and over 5,600 plants to ensure a biophilic environment is maintained and enhance biodiversity (P1). The design incorporates plant species not commonly used in public spaces, juxtaposing them with the falaj, an ancient irrigation system in the UAE. This geographically, culturally, and ecologically sustainable approach highlights the innovative falaj's cultural significance. (P5)

Passive cooling, ventilation, and shading strategies reduce the building's energy consumption, creating comfortable outdoor environments with shaded gardens and large pools (M3). Shaded arcades, protected by the sheltering form of the floating wings, allow for outdoor environments that are host to native and regionally adapted tree and plant species, highly functional and responsive to the region's hot climate. These passive strategies reduce energy use, especially for the prevailing cooling needs (P5).

DISCUSSION

Biophilic and biomimicry features can serve the sustainable agenda; the five cases discussed contain 60 features, each achieving 1-2 sustainable aspect(s), as shown in Table 8. This shows how integrating nature into the human-built environment can benefit the occupants and the natural environment. Future applications can attempt to cover more aspects in a strategy to promote the benefits of bio-inspired design strategies in buildings. This can be achieved by dedicated research into integrating nature's needs with human necessities. We can benefit the world and the human species by further understanding nature and how it works.

Table 8. Summary of patterns and their sustainability aspects. Source: The authors

Biophilic design	**Code**	**No. of applications**	**Sustainability aspects addresses**
Environmental Features.	P1	8	Energy efficiency Indoor environmental quality
Natural Shapes and Forms	P2	4	Energy efficiency Adaptability and flexibility
Natural Patterns and Processes	P3	4	Biodiversity Indoor environmental quality
Light and Space	P4	1	Energy efficiency
Place-Based Relationships	P5	6	Biodiversity Indoor environmental quality
Human-Nature relationship	P6	7	Indoor environmental quality Adaptability and flexibility
Biomimicry	Code	No. of applications	Sustainability aspects addresses
Evolve to Survive	M1	3	Biodiversity
Adapt to Change	M2	2	Adaptability and flexibility
Be Locally Attuned and Responsive	M3	6	Energy efficiency Water conservation
Integrate development with Growth	M4	5	Energy efficiency Biodiversity
Resource Efficient	M5	11	Energy efficiency Indoor environmental quality
Life-Friendly Chemistry	M6	3	Sustainable materials

CONCLUSION

The combination of biophilia and biomimicry in design represents a paradigm shift to peacefully integrate human and natural ecosystems. The reverence for life reveals itself in biophilic design, which smoothly incorporates nature into the structural composition of numerous buildings. Integrating sustainability concepts from the start of a project shows a commitment to harmonious relationships between built surroundings and ecological systems. This dedication supports sustainability.

Dubai Expo 2020 pavilions feature nature-inspired designs that promote sustainability and harmony with nature's beauty. Biomimetic design addresses interdisciplinary sustainability issues, promoting energy conservation and a deep connection with the natural world. Biomimicry demonstrates economic and environmental sustainability, showcasing the wisdom of nature and human inventiveness in interacting with nature.

The study examined the Dubai Expo 2020 pavilions' biomimetic application. These examples showed how these techniques may transform design through sustainability. These pavilions offered physical places and immersive experiences that reflected nature's dynamic and harmony by incorporating natural concepts and ideas.

Nature, biophilia, and biomimicry are fundamental concepts that create harmony in structures. As architects, creativity encompasses human connections, environmental sustainability, and a future where architecture becomes part of life's symphony rather than just shelter.

Authors' contribution: Conceptualization, I.I. and B.A.; Data curation, B.A. and I.I. ; Formal analysis B.A. ; Investigation, B.A. , Funding acquisition, I.I. ; Research, I.I. and B.A ; Methodology, B.A. and I.I.; Project Management, I.I.; Resources; Software; Supervision I.I. ; Validation, I.I. ; Visualization I.I. ; Writing - original draft, B.A.; Writing - review and editing I.I.e architecture becomes part of life's symphony rather than just shelter.

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REVIEW OF "LIGHTENED SLIPSTRAW CEILINGS" AS A CULTURAL PRACTICE IN THE VERNACULAR ROOFING OF AYMARA HOUSES IN ARICA AND PARINACOTA, CHILE[1]

RELEVAMIENTO DEL USO DEL "CIELO DE BARRO Y PAJA ALIVIANADO" COMO PRÁCTICA CULTURAL EN LA TECHUMBRE VERNACULAR DE LA VIVIENDA AYMARA DE ARICA Y PARINACOTA, CHILE

PESQUISA SOBRE O USO DO "TETO DE BARRO E PALHA ALIVIADO" COMO PRÁTICA CULTURAL NO TELHADO VERNACULAR DAS RESIDÊNCIAS AIMARÁS EM ARICA E PARINACOTA, CHILE

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1 Project No. 49204, Cultural Heritage Fund, Ministry of Culture, Arts and Heritage, call for proposals 2021.

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RESUMEN

Este artículo trata acerca de la caracterización de la tecnología de un cielo raso de paja y barro denominada en lengua aymara como "caruna". El estudio se realizó en viviendas Aymaras a más de 4.000 metros sobre el nivel del mar en la localidad de Tacora, en la región de Arica y Parinacota, Chile. El estudio forma parte del proyecto 49204 financiado por el Servicio Nacional del Patrimonio Cultural. Su objetivo es rescatar esta técnica vernácula como alternativa a los materiales industrializados que han modificado la vivienda andina y la calidad de vida en climas extremos durante los últimos 25 años. Se recogieron muestras de los materiales utilizados en esta técnica, reproducida por un cultor local, y se analizaron en laboratorio para determinar sus propiedades térmicas y de trabajabilidad. Además, se monitoreó el desempeño energético de tres viviendas en el poblado de Tacora para comparar los resultados obtenidos con los de los laboratorios. Los hallazgos revelaron que la matriz de barro utilizada en esta técnica de encielado es predominantemente arcillosa con mediana compresibilidad y baja conductividad térmica, lo que la hace adecuada como aislante en climas desérticos fríos. El cielo de barro y paja alivianado se destacó por su presencia en la cultura local, la disponibilidad de recursos materiales y su facilidad de instalación. Este estudio subraya la importancia de preservar el conocimiento tradicional, respetando los saberes ancestrales y mejorando el desempeño térmico de las viviendas en la cordillera norte de Chile, Perú y Bolivia, destacando su relevancia para el desarrollo de soluciones habitacionales sostenibles y culturalmente pertinentes.

Palabras clave
construcción en tierra, arquitectura vernácula, fibras naturales, aislación térmica, Ichu.

ABSTRACT

This article reviews the slipstraw ceiling technology known in the Aymara language as "caruna." The study was made in Aymara homes at more than 4,000 meters above sea level in the town of Tacora, in the region of Arica and Parinacota, Chile, as part of project 49204, financed by the National Cultural Heritage Service. It aims to recover this vernacular technique as an alternative to industrialized materials that have modified Andean housing and the quality of life in extreme climates over the last 25 years. Samples of materials used in this technique, reproduced by a local craftsman, were collected and analyzed in the laboratory to determine their thermal properties and workability. The energy performance of three homes in Tacora was also monitored to compare the results obtained with those of the laboratories. The findings revealed that the mud mold used in this ceiling technique is predominantly made from clay with medium compressibility and low thermal conductivity, which makes it apt for insulation in cold desert climates. Lightened clay and straw ceilings stand out in the local culture thanks to the availability of material resources and ease of installation. This study highlights the importance of preserving traditional knowledge, respecting ancestral knowledge, and improving the thermal performance of homes in the northern mountain range of Chile, Peru, and Bolivia, highlighting its relevance for developing sustainable and culturally relevant housing solutions.

Keywords
earth construction, vernacular architecture, natural fibers, thermal insulation, Ichu.

RESUMO

Este artigo trata da caracterização da tecnologia de um teto feito de palha e barro, conhecido na língua aimará como "caruna". O estudo foi realizado em habitações aimarás a mais de 4.000 metros acima do nível do mar na cidade de Tacora, na região de Arica e Parinacota, Chile. O estudo faz parte do projeto 49204, financiado pelo Serviço Nacional de Patrimônio Cultural. Seu objetivo é resgatar essa técnica vernacular como uma alternativa aos materiais industrializados que modificaram as moradias andinas e a qualidade de vida em climas extremos nos últimos 25 anos. Amostras dos materiais usados nessa técnica, que foi reproduzida por um cultor local, foram coletadas e analisadas em laboratório para determinar suas propriedades térmicas e de trabalhabilidade. Além disso, o desempenho energético de três casas no vilarejo de Tacora foi monitorado para comparar os resultados obtidos com os dos laboratórios. As descobertas revelaram que a matriz de barro usada nessa técnica é predominantemente argilosa, com compressibilidade média e baixa condutividade térmica, o que faz com que seja adequada como isolante em climas desérticos frios. O telhado de palha e barro destacou-se por sua presença na cultura local, pela disponibilidade de recursos materiais e pela facilidade de instalação. Este estudo ressalta a importância de preservar o conhecimento tradicional, respeitar o conhecimento ancestral e melhorar o desempenho térmico das habitações na cordilheira norte do Chile, Peru e Bolívia, destacando sua relevância para o desenvolvimento de soluções habitacionais sustentáveis e culturalmente relevantes.

Palavras-chave:
construção em terra, arquitetura vernacular, fibras naturais, isolamento térmico, Ichu.

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INTRODUCTION

A revision of the Population and Housing censuses of the Region of Arica and Parinacota in the last 25 years demonstrates the existence of a substantial change in the composition of the materials used in the roofs of the Aymara vernacular dwellings (Figure 1), which, in turn, could have carried out a process of change in their efficiency and effectiveness in the face of the extreme climate where they are located.

Several investigations in cultural anthropology between 1968 and 1969 in Enquelga (Chile) found evidence of the use of mud and straw in the ceilings of Aymara houses. In this ethnographic record, 90 dwellings were identified where the use of the local technique called "[...] Caruna" or "Karuna" (Šolc, 2011; Weber et al., 1998), or also "takta" (Figure 2 and Figure 3), which was the traditional way used to put on a roof in the Andean highland villages in northern Chile (Šolc, 2011).

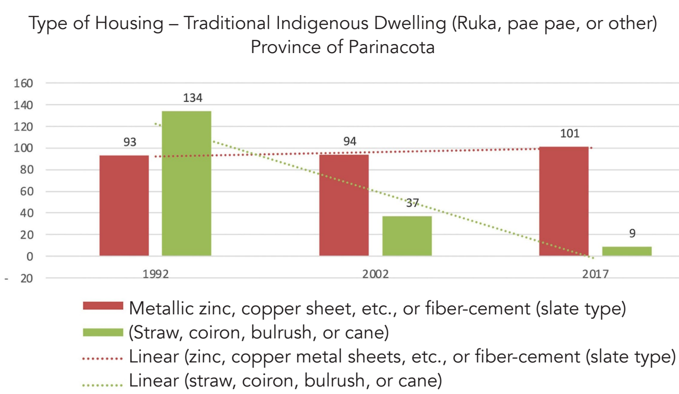
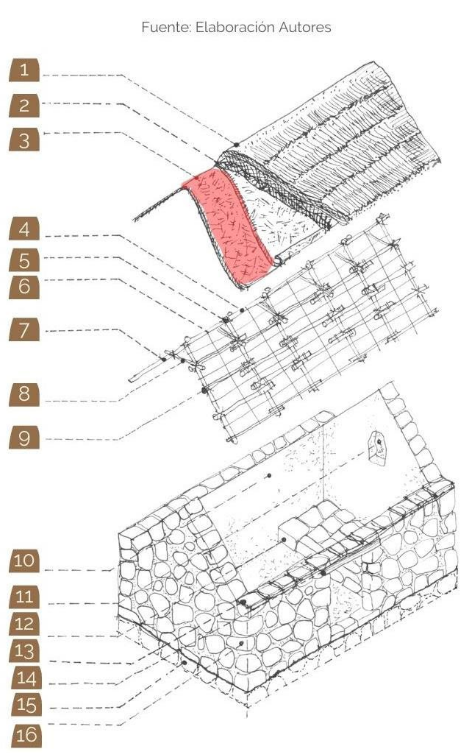


Figure 1. Analysis of the material substitution between vegetation-based roofing to zinc plates or fiber cement, "traditional indigenous" housing, Province of Parinacota, intercensal periods 1992-2002-2017. Source: Preparation by the authors

Figure 2. A ceiling of a traditional house in Guallatire, "caruna" or "takta," the material under study is white; photograph from 2022. Source: Preparation by the authors



Elements and parts of Traditional Andean housing found above 4,000 m.a.s.l, case of Guallatire, Arica and Parinacota, Chile

1. Outdoor roof, reed grass, mud-plastered, 10 to 15 cm, built with a 'fort' and 'fish-scale' perimeter protective eave.
2. Intermediate loose reed grass layer, with a regular 20 cm thickness
3. Indoor ceiling (Caruna, Karuna, takta, píra, tíli, slipstaw, 1 to 2 cm.
4. Ridge beam – Unworked queñoa wood, app. diam- 7 cm
5. Secured in an "x" shape called "correhuela," by damp llama leather
6. Sub-structure – llama leather straps – 1 cm
7. Truss structure – unworked Queñoa wood, app. diam. 7 cm
8. Knuckle or latch – unworked Queñoa wood, app. diam. 5 cm
9. Girts or "quiras" - unworked Queñoa wood, app. diam. 7 cm
10. Wall coating: sandy clay, possibly including lime.
11. Niche for bedhead wall, also called "phutu", Pre-Incan origin
12. Laminated above ground, allows placing a bed
13. Flagstone struts with volcanic, ignimbrite, or similar rocks
14. Sawn wood lintel
15. Continuous foundation on large sized stone, that jut 0.15 to 0.20 cm out of the ground, high density rocks, igneous type.
16. Quarried cyclopean corner rock blocks. The wall in general is built with two faces, with rocks split with their smooth or quarried face facing outwards. The wall is 35 to 40 cm thick.

Figure 3. Traditional housing in Guallatire incorporating the use of "Caruna or Takta". Source: Preparation by the authors

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Figure 4. Plan of Tacora, August 2022, overview of the village, walls, and ceilings of houses considered for the indoor climate study. Source: Preparation by the authors

This constructive system reveals social, cultural, and ritual implications in establishing an adaptive strategy to the physical-climatic environment of living at altitude. The last time this constructive system was mentioned was in the '70s, thanks to the research made by Dr. Václav Šolc in the town of Enquelga.

The presence of mud and straw ceilings has been mentioned recently in the context of ethnobotany studies. In this field, when considering that Aymara architecture is an adaptive response to the extreme environment, many authors have risked characterizing Andean housing as "[...] one that has common characteristics and repetitive typological patterns throughout the Andean macrozone, which have been widely described by numerous architects, anthropologists, and architectural historians" (Jorquera, 2014).

In 2018, after the restoration of the town of Tacora, this technique was reintroduced, although this time incorporating industrialized, standardized materials and combined with the vernacular technique. This phenomenon constitutes the case study discussed in this article (Figure 4 and Figure 5).

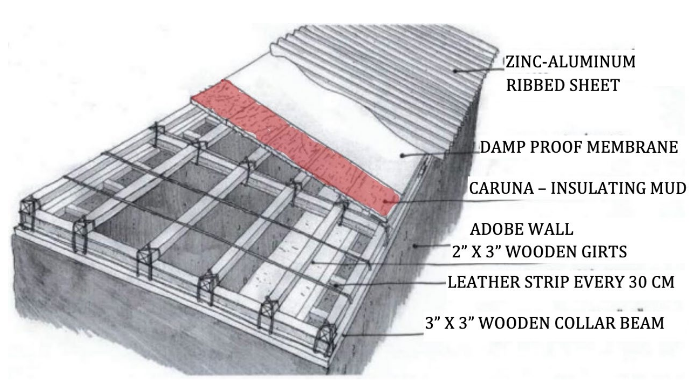

Figure 5. Construction isometrics for a house restored in Tacora in 2018. Source: adapted by the authors from Fundación Altiplano

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POTENTIAL OF THE "CARUNA" CONSTRUCTIVE TECHNIQUE

The Aymara "Caruna" or "Takta" construction technique uses a lightened 1 to 2-cm thick clay and straw sheet, sized into 50-cm wide strips, which are placed, slightly overlapping, on a reed lattice, with a smooth inner surface. Its preparation is done on-site, with fine straw and mud rammed under a cloth to compress it (Directorate of Architecture, Ministry of Public Works, 2016).

The combination of mud and straw, called "lightened earth," has been linked to mixed systems of load-bearing wooden structures. In some European countries, such as Germany or France, these have been used for a long time in a modern way, in compliance with regulations, achieving a good thermal and acoustic performance (Meli et al., 2019). However, their seismic behavior still needs to be evaluated.

From a more ecological point of view, making clay and straw sheets for roofing is related to the cycle of the Andean pastures. The houses' roofs are constructed before flowering, as the Andean grass species with which the lightened clay and straw are made have better performance and durability when harvested at this stage. The grass species used for straw include reed grass and Peruvian feathergrass, commonly used in the ceilings and roofs of houses in the Andean sector (García et al., 2018).

On the other hand, diverse research on the effect of artificial and natural fibers on soil behavior has reported that these fibers are efficient and low-cost soil-stabilizing materials. It has also been found that the fibers' tensile strength and elongation are greater when wet (Charca et al., 2015).

THERMAL AND MECHANICAL PROPERTIES

The "Caruna," as a mixed construction system, has interesting thermal and mechanical properties for current construction. Some research, such as that conducted by Weiser et al. (2020), Volhard (2016), and Vinceslas et al. (2019), has established that the thermal properties of mixed lightened mud and straw construction systems have great potential as an insulator, coating or filling in wall partitions or roofing. As for their thermal performance, this largely depends on the density of the mud and straw mix. However, the possibility has been raised that, with densities over 1200 kg/m^3, thermal yields close to 0.150 W/mK can be obtained (Meli et al., 2019).

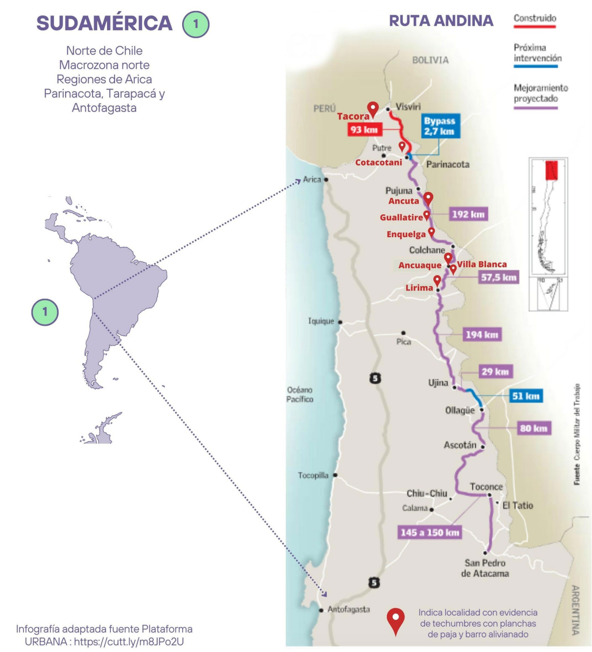

Figure 6. Case study location. The cases from Tacora to Guallatire are found along the A-23, 11, A-211, and A-235 routes of the Province of Parinacota. Source: Adaptation by the authors of the urban platform infographic.

Finally, regarding mechanical strength properties, it has been shown that both the selection and arrangement of the straw fibers improve the material's mechanical strength within the mud mix (Noaman et al., 2020).

RESEARCH FRAMEWORK AND CASE STUDY

This article is part of the actions undertaken in the research project called "Caruna: Technological Rescue of Sustainable Vernacular Knowledge for Thermal Insulation in the Andean Architecture of Arica and Parinacota," made thanks to obtaining the 2021 Cultural Heritage Fund in the sub-modality of cultural heritage research, registration, and review.

The general goal of the research project was to expand the knowledge to safeguard "Caruna" as ancestral knowledge and the material expression of the constructive practice of the Andean world, which currently has no official identification and is in danger of disappearing from the constructive repertoire of the communities and the vernacular architecture of the Arica and Parinacota region.

The study area is located in the high Andean zone of the Arica and Parinacota Region, at more than 4000 m.a.s.l., specifically in the towns of Tacora, Guallatire, Ancuta, Chua, and Misitune, which are

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part of the General Lagos and Putre commune and are located immediately to the west of the Andes Mountain Range (Figure 6). In this area, the climate is that of the typical high-altitude marginal desert, classified as BWk in the Köppen-Geiger taxonomy (Peel et al., 2007), where the temperature can reach minimums of -15 °C and maximums of 25 °C, with very high levels of solar radiation (more than 1000 W/m^2 at noon for almost the whole year) and rainfall concentrated in January and February (Figure 7 and Figure 8).

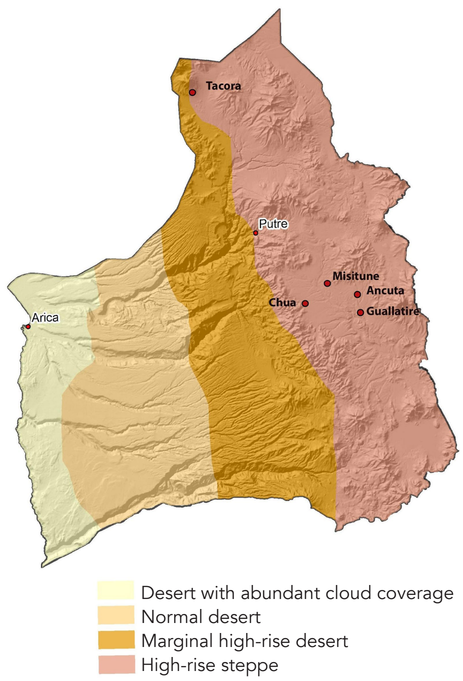

Figure 7. Climatic characterization - High Andean, Arica and Parinacota Region. Source: Base map http://www.gep.uchile.cl

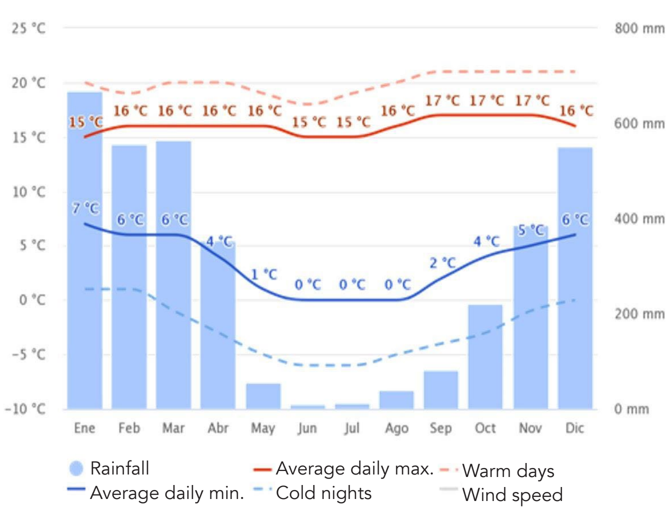

Figure 8. Average temperatures and rainfall. Historical climate and weather data of Tacora. Source: Meteoblue

The case study is located in the town of Tacora, which gets its name from the volcano on whose slopes it sits, which borders with Peru. This sector is characterized by an extraordinary natural and cultural landscape marked by the conditions of a high-altitude desert. Its origin dates back to the Inca colonial formations that took place during the 16th century in response to the advance of the Spanish crown within the territory, giving rise to the homesteads of Ancomarca, Cosapilla, and Tacora. It received influence from the Silver Route and, more recently, in the 19th century, it had its economic heyday linked to sulfur extraction and the connection with the Arica to La Paz railway. From 1967, the extraction of the mineral ceased, and migration to the nearest urban center of Arica began, which continues to this day. Tacora has a permanent population of 4 people, and many others move from the city to the village to celebrate the patron saint festivities of the Virgen del Carmen (Pereira & Yuste, 2019).

METHODOLOGY

The methodology applied for this study can be divided into four stages. The first is related to making a bibliographic study and a review of information to confirm the presence of different roofing materials in homes in the area of interest. Then, in the second stage, surveys were made to establish the degree of knowledge transferred between generations of residents in the province of Parinacota regarding the construction techniques associated with vernacular roofs. In the third stage, samples of material identified as "Caruna" were obtained, and microscopic characterization and thermal behavior tests were performed on them. Finally, in the fourth stage, studies were made to monitor the thermal behavior of two houses with different insulation materials.

STUDY METHODOLOGY STAGES

First Stage: Confirmation of Roofing Materials

The first stage consisted of making a 25-year longitudinal study on replacing roofing materials in rural areas of the province of Parinacota. To do this, the data obtained from the Population and Housing Censuses of 1992, 2002, and 2017 were analyzed, focusing on two categories: a) Housing identification typologies used by the INE (National Statistics Institute), and b) material typologies that make up the different parts of the house.

The analysis consisted of reviewing each of the intercensal periods and then cross-checking

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information based on specific types of materials such as "straw," "coiron," "bulrush," and "sugar cane."

Second Stage: Knowledge Transfer between Generations

To clarify the effectiveness of knowledge transfer between generations, the first task was to contact the locally schooled young population to determine their knowledge regarding the traditional way of making the "lightened slip-straw ceiling." For this work, the (intentional) sample chosen was 32 students aged 16-17 from the Agrícola Granderos de Putre Technical High School.

This is because strong state policies, instilled in the last two decades to promote the recognition of indigenous peoples, have resulted in a tendency among young people to affirm ethnic identities, which leads to valuing the past, recovering rituals, and resignifying them in urban spaces (Gavilán & Vigueras, 2020; Yáñez & Capella, 2021).

The methodology included, first of all, a theoretical presentation of the material's characteristics, its relevance, and the description of the research (Figure 9). Secondly, to determine the constructive knowledge among the Andean youth, a survey was used considering ten questions divided into two dimensions (Table 1). The first dimension identified previous knowledge about the construction technique, which adopts different names depending on the village's location. These names were obtained from an earlier literature review. The second dimension aimed to clarify the motivation and interest of perpetuating the constructive tradition. In this case, the assertions had a binary answer choice (yes-no).

Figure 9: Milestone of the Launch of the project in the town of Putre, August 2022, application of measuring instrument on constructive knowledge. Source: Preparation by the authors

Table 1: Dimensions of the survey that asks about previous knowledge and the projection of perpetuation of knowledge by the young people of the town of Putre. Source: Preparation by the authors

Dimension 1: Identification of Prior Knowledge.	Dimension 2: Motivation and Interest to Perpetuate the Constructive Tradition.
1. I have heard the term "caruna" before.	6. There is a lot of talk about this type of roofing in my family.
2. I have heard the term "tacta" before.	7. I know other typical construction methods for making roofs.
3. I have heard the term "p'ira" before.	8. I value constructive knowledge that is typical of the local culture.
4. I have heard the term "t'ili" before.	9. I would be interested in learning about these construction methods.
5. I know that any of these terms ("caruna," "tacta," "p'ira," "t'ili") are part of some traditional customs.	10. I would be interested in knowing more about Andean architecture.

Third Stage: Determination of Thermal Properties of the "Caruna"

To obtain samples of "Caruna," a mason from the village of Visviri was contacted (Figure 10), who recovered this knowledge from his personal experience and allowed this technique to be incorporated into the restoration of the village of Tacora in 2018. A first-source account was obtained from him about his perspective and assessment of this constructive knowledge, and he also made two "caruna" samples. These samples were subsequently tested in the CITEC laboratory under the NCH 850 Standard Of 2008.

According to the laboratory report, the samples analyzed were defined as a natural material made using slipstraw, referred to by the customer as "Caruna," sized 30cm x 30cm x 0.5 cm, with an apparent dry density of 1252 kg/m^3. On the other hand, to obtain the transmittance and resistivity values of the constructive solution, the guard ring method was used according to the procedure described in the same Standard.

The standardized test consists of a central metal plate (hot plate) provided with electric heating. This plate is surrounded by a frame (guard ring), which can be heated independently. The samples

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Figure 10: Aymara mason preparing the samples to be sent to the laboratory. Source: Preparation by the authors

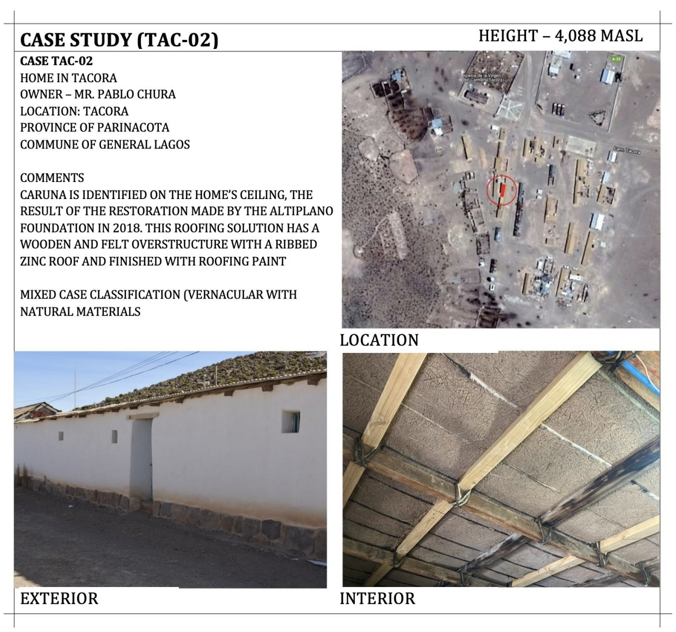

Figure 11. Houses restored with a slip-straw ceiling, Tacora, 2022. Source: Preparation by the authors

(2) are arranged on both sides of the plates, of equal dimension, and with parallel flat faces. The respective water-cooled metal plates (cold plates), whose shape is similar to that of a sandwich, are located adjusted to the samples.

Fourth Stage: Monitoring the Hygrothermal Behavior

As mentioned above, this study was carried out in the town of Tacora since, on the one hand, there was a contemporary and recent intervention in the use of the caruna in the restoration of the village in 2018. On the other hand, in this village, it was

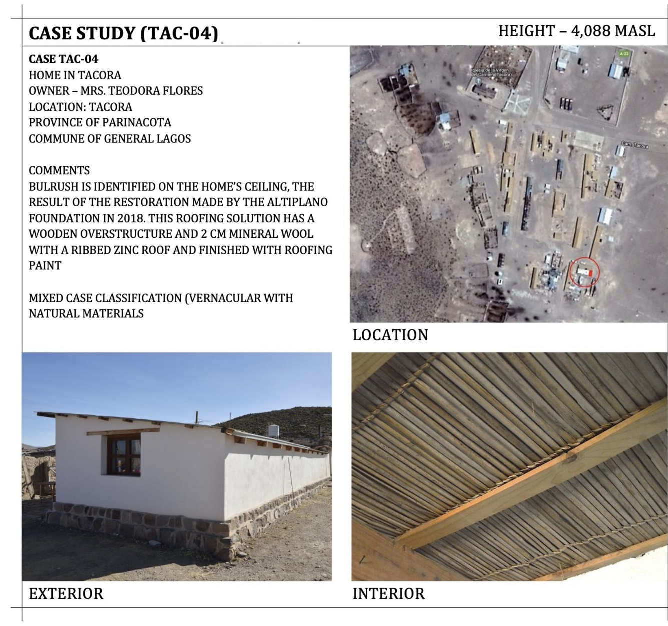

Figure 12. Houses restored with a bulrush ceiling, Tacora, 2022. Source: Preparation by the authors

possible to have a contrast material that is also used in the ceiling because it is considered a good thermal insulator, known as "Totora" or bulrush (Aza-Medina et al., 2023; Hidalgo-Cordero et al., 2023).

Four houses were initially chosen to make this contrast: two with a "slip-straw" ceiling and two with a "bulrush" ceiling. Then, a new selection was made, choosing one of each to be monitored (Figure 11 and Figure 12). This process was oriented, first of all, to obtain environmental comfort parameters and data using temperature and humidity variables of the indoor-outdoor climate of the houses that use bulrush, to subsequently compare them with environmental comfort simulations of the houses from the obtaining normalized thermal transmittance data of the "slip-straw" material.

DATA COLLECTION

As for collecting climate data, these were obtained through a planned field campaign to measure the indoor and outdoor environmental behavior of homes accurately. This campaign identified the points of interest and the tools and equipment needed to collect the information inside and outside the homes.

Inside the four houses chosen, temperature and humidity measuring equipment (Datalogger) were installed and positioned at a roof level. The equipment installed comprises small registration thermographs that allow storing a large amount of data for extended periods. The equipment was configured for this research to obtain information every 15 minutes for 5 months (July-November). A comfort measuring station (Testo 400) was also used, which included:

- a globe thermometer for measuring the average radiant temperature
- a hot-wire anemometer for measuring air velocity
- a thermometer for measuring room temperature
- a hygrometer for the measurement of relative humidity
- a processor recorder for the calculation of the expected mean vote

The process to determine the location of the equipment consisted, first of all, of measuring the enclosure where the equipment would be located with a laser meter. This measurement included the area of the room, the windows and doors, and the height of the dwelling. The position where the Datalogger would be located was determined from the information obtained. An attempt was made to keep the equipment focused on the room and away from any source of heat and humidity that could alter the general data. It was fastened with ropes to the roof beams for its installation, and the start of the data reading was inspected. Finally, the equipment code and its position in the room were recorded. On the other hand, for installing the TESTO 400 equipment, it was determined to consider five established measurement points and two registration heights at each point because the indoor environment was not homogeneous.

A digital weather station with a base station and sensors was installed outside the houses to obtain the measurement values. These sensors were located at a measuring point on a mast at a height of four meters. The information obtained by the sensors was sent to the base station through a display console located inside the house, and from there, a real-time reading was obtained through the Wi-fi signal. In addition, the connection of the weather station with one of the team's mobile devices was established to monitor the correct operation of the station and preview the data stored by the sensors. This made it possible to make a first approximation of the recorded meteorological fluctuation.

Table 2 summarizes the technical specifications of each piece of equipment used to measure temperature, humidity, and comfort inside and outside the monitored homes.

Table 2. Detail of the instruments used in the housing monitoring phase. Source: Preparation by the authors

Equipment	Technical specifications
Datalogger Temperature (t°) and Humidity (H%) Elitehc	T° measuring range: +60°C ~30°C (Internal sensor) -40°C~+85°C (external) H% range: 10% - 99% Accuracy: ± 0.5°C Resolution: 0.1°C Size: 84mm x 44mm x 120mm
Testo 400 set comfort multifunction instrument	Digital CO2 probe -Digital turbulence degree probe -150 mm globe probe, TP type K, for measuring radiant heat
Wireless Communication Weather Station 111-METWIFI	Indoor t° range: 0°C to 50°C Outdoor t° range: -30°C to 65°C H% range: 1% – 99% RH Anemometer wind speed: 0-50 m/s Rain gauge: 0 - 9,999 mm Brightness range: 0-400,000Lux Pressure: 300 – 1100 hPa

RESULTS AND DISCUSSION

LIST OF MATERIALS USED IN ROOFS

The analysis of census data from the 1992-2017 period on the materiality of housing focused on the province of Parinacota and showed a decrease in the presence of plant materials as insulators in the roofs of housing. This statement is reflected in Table 3, which shows that out of a total of 180 homes surveyed between 1992 and 2017 and classified as "indigenous housing," in 1992, there were 134 homes (74% of the total sample analyzed) that used this type of insulating material. In 2002, this number was reduced to 37 homes (20.5%), and in 2017, only nine houses had vegetable insulation on their roofs, representing 5% of the total.

The analysis also determined an inversely proportional relationship between using plant materials and the roofing materiality coated with metal or composite sheets (zinc, copper, fiber cement). This type of roofing is initially and primarily related to the kind of housing classified as a "house" and, to a lesser extent, with "traditional indigenous housing." However, in 25 years (1992 – 2017), the total number of homes with a roof made of zinc plates and fiber cement reached 929, showing a progressive increase in the presence of these materials in the highland areas (Table 4).

Table 3. Roofing material: Straw, coiron, bulrush, or cane, Province of Parinacota, (Rural) - Population and housing census data for 1992, 2002, and 2017. Source: Preparation by the authors

Presence of vegetation-based roofing in different types of housing	1992	2002	2017
Other types of private housing	0	0	0
Single-slope roof, improvement, ranch, or pent-roof	1	0	0
Room in an old house or tenement	0	0	0
Indigenous Housing (Ruka, pae pae, or other)	134	37	9
House	23	0	0

Table 4. Roofing material: zinc plates, copper, fiber cement, etc. Province of Parinacota (Rural) Data Population and Housing Censuses for 1992, 2002, 2017. Source: Preparation by the authors

Presence of zinc plates, copper, fiber cement, etc., in different types of housing	1992	2002	2017
Other types of private housing	2	3	3
Single-slope roof, improvement, ranch, or pent-roof	2	32	11
Room in an old house or tenement	1	16	2
Indigenous Housing (Ruka, pae pae, or other)	93	94	101
House	314	378	237

Regarding the materiality of the exterior walls, 36.36% are brick houses, 27.27% are stone and clay, and the remaining 36.36% are adobe. Compared with the data provided by the INE regarding the roofing material composition, this sample indicates that even though the leading roofing material is zinc sheeting, the ceilings of traditional homes have a high percentage of straw and mud.

TRANSMISSION OF KNOWLEDGE BETWEEN GENERATIONS

Analyzing the data obtained through the surveys, it can be confirmed that the students are mostly unaware of this constructive technique. For example, the question about whether they know the term "t'ili" obtained 24% recognition, this being the most well-known technique. On the other hand, the question about the association of any of these terms ("caruna," "tacta," "p'ira," "t'ili") with roofs, obtained 67% of mentions (Figure 13).

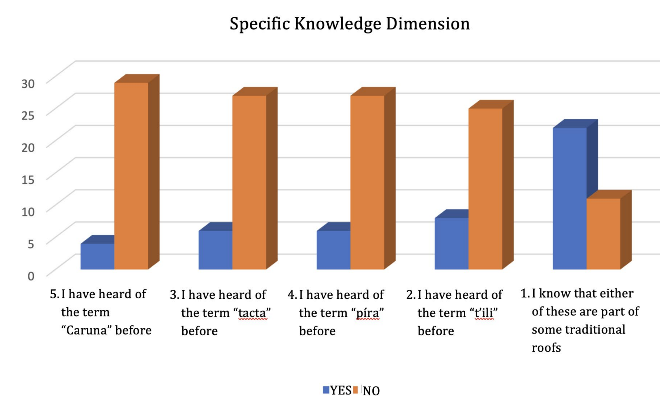

Figure 13. Association between the name of the construction system and the local names of the "lightened slip-straw" technique among Putre's younger population. Source: Preparation by the authors

Regarding the second dimension, a lack of knowledge of the caruna and the other general typical construction techniques can be identified, as, in both points, more than half of the surveyed population refers to not knowing about them (67% and 55%, respectively). This situation contrasts with 97% who find value in this knowledge and 85% who directly express interest in learning about this and other traditional Andean construction techniques (Figure 14).

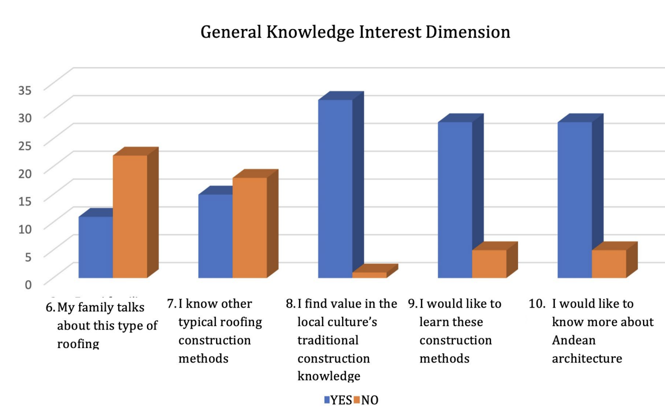

Figure 14. The number of responses from students regarding the assessment of typical local culture constructive systems. Source: Preparation by the authors

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RESULTS

THE TESTS AND MONITORING WORK

To determine the thermal behavior of a composite material, as in this case, a laboratory test result is needed that can be used in the construction permit procedures, as indicated by current regulations (MINVU, 2006).

For the case of "caruna", the sample tested in the laboratory consisted of a natural material made from mud straw, 30 cm x 30 cm x 0.5 cm in size, with an apparent dry density of 1252 kg/m^3. The laboratory test was run following the NCh 851 standard. In this, the sample reached a linear thermal conductivity value of 0.1477 W/mK. Regarding its apparent density (Table 5) and characterization as a lightened material, the reference value obtained is above 52 gr., as Wieser et al. (2020) pointed out.

Table 5. NCh 851 Linear thermal conductivity test results - "Caruna" (mud-straw) test piece. Source: Preparation by the authors

Linear thermal resistance (r)	0,0359	(m K/ W)
Thermal conductivity (λ)	0,1477	(W/ m K)
Dry material density (δ)	1252	(Kg/m 3)
Material humidity (H)	22,32	(%)

Table 6 shows the linear thermal conductivity reference values. According to the results obtained through laboratory testing, the data on the value result for the "caruna" test piece is located within the range of materials with available standardized information. The table's data indicate for the transmittance values that the greater the magnitude, the lower the insulating capacity the material has. An enclosure with a good insulating material (5-8 cm) reaches transmittance values of around 0.6-0.4 W/m^2 K.

The roofing enclosures commonly used in Andean dwellings are lightweight zinc, clay tile, or wooden roofs. In some cases, the use of concrete slabs in recently built housing is observed. The lightweight roof used by caruna achieves a better thermal performance than uninsulated slabs and is comparable with earthen or wooden roofs. As for sheet metal roofs, the advantage is even more significant, improving the value of the thermal wave lag, which is an indicator of the thermal inertia of

Table 6. Reference values of transmittance and thermal lag for roofs. Source: Preparation by the authors

Material	Thickness (cm)	Transmittance (W/m2 K)	Time Lag
Caruna 5 mm + fieltro 1 mm + zinc 2 mm	0,8	5,75	30 min
Caruna 10 mm + fieltro 1 mm + zinc 2 mm	1,3	4,76	40 min
Caruna 20 mm + fieltro 1 mm + zinc 2 mm	2,3	3,63	1 h 30 min
Cement roof	15	4,48	2 h 50 min
Zinc roof	0,2	7,14	1 min
Earth roof	7	3,6	1 h 11 min
Wooden roof	5	2,56	1 h 30 min

the roof. This result is aligned with the results obtained by other similar studies (Palme et al., 2012; Palme et al., 2014) that show that, by increasing the thickness of the caruna, the thermal performance can improve proportionally, being able to reach and exceed the thermal resistance values typically offered by wooden roofs or with other natural insulators such as, for example, cork.

Figure 15, on the other hand, shows the monitoring results for a typical day in July, with indoor temperature oscillations between 1 and 22 degrees, both for the "caruna" roof and the bulrush roof. Although this result shows a certain degree of night cooling below levels considered acceptable to being in comfort, it evidences that the thermal insulation offered by the caruna is similar to that provided by other materials traditionally used in housing roofs of the high Andean areas.

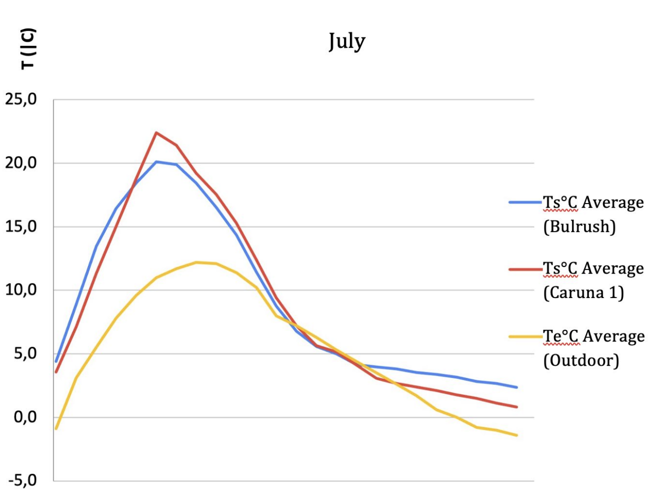

Figure 15. Performance monitoring chart, a typical day in July. Source: Preparation by the authors.

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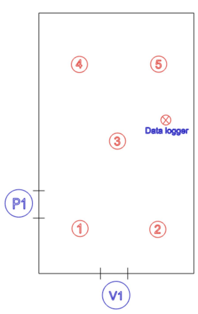
Regarding comfort monitoring, Figure 16 and Figure 17 show the results obtained in the measurements carried out in July 2022 with the TESTO 400 equipment. In these, values of 70 W/m^2 were used as metabolic activity and 1 CLO as thermal resistance of clothes to estimate the predicted mean vote (PMV), the standard measurement of the degree of comfort in indoor spaces (Fanger, 1973). Despite a time lag in the data collection, the results show a somewhat better thermal behavior for the "caruna" roof, with radiant average temperatures between 18 and 20 degrees Celsius, confirmed in a PMV indication of -0.8 (slightly cool environment).

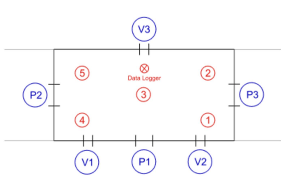
Case 1: "Bulrush" ceiling (natural fiber)



		INICIO MEDICIÓN:		10:10 am		
PUNTO DE MEDICIÓN		Ta (ºC)	TMR (ºC)	HR (%)	v (m/s)	PMV
INFERIOR	P1	12,8	15,9	33	0,1	-1,63
	P2	11	15,8	36	0,1	-1,82
	P3	11,3	14	33	0,1	-1,98
	P4	11,4	14,8	34	0,1	-1,89
	P5	11,5	15,2	33	0,1	-1,84
SUPERIOR	P6	10,8	15,9	34	0,1	-1,84
	P7	11,1	15,8	37	0,1	-1,81
	P8	11,4	14,4	32	0,1	-1,93
	P9	11,5	15	39	0,1	-1,84
	P10	11,5	15,3	36	0,1	-1,82

Figure 16. Floor plan of the house with "bulrush" ceiling indicating data collection points. Source: Preparation by the authors.

Case 2: "Caruna" ceiling (lightened slip-straw)



		INICIO MEDICIÓN:		12:00 pm		
PUNTO DE MEDICIÓN		Ta (ºC)	TMR (ºC)	HR (%)	v (m/s)	PMV
INFERIOR	P1	17,7	20,6	29	0,1	-0,65
	P2	17,3	19,9	26	0,1	-0,79
	P3	17	19,8	29	0,1	-0,81
	P4	16,9	19,9	28	0,1	-0,81
	P5	16,8	20	30	0,1	-0,81
SUPERIOR	P6	17,5	20,9	30	0,1	-0,64
	P7	17,1	19,8	31	0,1	-0,79
	P8	17	19,8	31	0,1	-0,8
	P9	16,8	20	33	0,1	-0,79
	P10	16,7	20,1	40	0,1	-0,76

Figure 17. Floor plan of the house with "caruna" ceiling indicating data collection points. Source: Preparation by the authors.

CONCLUSIONS

This research has allowed us to rediscover a constructive ancestral knowledge defined as "lightened slipstraw ceiling," which has good thermal insulation characteristics compared to other materials that fulfill a similar role. The results allow resuming the ethnographic discussion in the 1970s in the Andean highlands and link it with the revaluation and reappropriation processes of the traditional ways of living at altitude. Undoubtedly, the safeguarding and dissemination of this knowledge will allow paying attention to how to preserve a material, symbolic, and domestic tradition that has been presented as a strategy against the extreme climate of the high-altitude tundra in the context of the desert above the altitude of 4,000 m.a.s.l.

From the perspective of the technological reappropriation of ancestral knowledge, in the small sample regarding Andean youth's knowledge of these, a clear representation of the risk of losing this other knowledge due to their lack of transmission could be found. However, fortunately, young people express their willingness and interest in approaching this type of learning, opening an essential space for conserving the constructive tradition. With this, two key points can be identified that give more strength and value to the realization of this project and increase the possible positive impact on the perpetuation and safeguarding of the use and practice of the elaboration of the "caruna" or "lightened slip-straw sheeting."

The longitudinal reading of the data on the composition of roofing materials obtained from the Population and Housing Censuses of Chile, taken in 1992, 2002, and 2017 for the Province of Parinacota, has made it possible to see the impact of the technological substitution of roofing materials in the typology defined by the INE as "traditional indigenous housing." This shows a drastic drop in the use of natural materials in contrast to the increased use of industrialized materials such as zinc and other sheets no larger than 1.10 m long. Despite these results, the recurrence of lightened slip-straw sheets is also highlighted as a common practice in the definition of the Andean housing space at altitudes above 4,000 m.a.s.l.

As for the material's thermal properties, the tests carried out have shown that the resistance value of the compound to the passage of heat is more than acceptable for a natural insulator, which translates into an onsite performance similar to that of other traditional structures. The possibilities offered by Caruna regarding the sustainability of the housing construction process in high Andean villages are very high, thanks to its mixing of local mud and straw. Modern sandwich-type roofs, even if they can incorporate insulating materials, will have a higher environmental cost due to the impacts generated by manufacturing and transportation at the installation site. Even the bulrush requires material displacements of a few hundred kilometers to be installed in the towns of Tacora, Guallatire, and their surrounding areas.

Finally, it is estimated that the lightened ceiling manufacturing processes can be gradually transformed into more consolidated processes so the ancestral knowledge of craft techniques can be incorporated with the most contemporary ones. However, more is needed to ensure that a highly industrialized product is reached that would significantly increase the environmental impact. On the contrary, the appropriate management of knowledge and its transfer between generations, as well as the eventual presence of some small local enterprise that is respectful of the fragile ecosystem of the Andean desert, could contribute to the consolidation of the manufacture, distribution, and use of this important material as a natural thermal insulator for constructions located in these towns and, more in general, in the entire highland macro-region.

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Construcción de modelos matemáticos simples para el cálculo del requerimiento energético de edificaciones
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BUILDING SIMPLE MATHEMATICAL MODELS TO CALCULATE THE ENERGY REQUIREMENTS OF BUILDINGS[1]

CONSTRUCCIÓN DE MODELOS MATEMÁTICOS SIMPLES PARA EL CÁLCULO DEL REQUERIMIENTO ENERGÉTICO DE EDIFICACIONES

CONSTRUÇÃO DE MODELOS MATEMÁTICOS SIMPLES PARA CALCULAR OS REQUISITOS DE ENERGIA DE EDIFICAÇÕES

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RESUMEN

El presente trabajo tiene por objetivo desarrollar un modelo matemático predictivo que otorgue un primer acercamiento al valor de requerimiento energético (RE) de un edificio en un clima templado continental, con el propósito de aportar al conocimiento teórico sobre herramientas de evaluación energética. Se realizaron simulaciones paramétricas procesadas con los programas *EnergyPlus* 9.5 y *JePlus*. Los resultados fueron utilizados como *Dataset* para el armado de diferentes modelos matemáticos, para los cuales se utilizó el programa SageMath a fin de desarrollar ecuaciones que predigan el RE de cada escenario. Se trabajó con modelos escalonando su complejidad en cuanto a métodos utilizados y cantidad de parámetros. Se seleccionó un modelo con bajo nivel de error (0.08) y 15 parámetros. Se advirtió que, si bien el aumentar la cantidad de parámetros acercaba los modelos al error 0.02, se corría el peligro de *overfitting*. El modelo seleccionado busca incorporar la precisión y validez de las simulaciones dinámicas a una herramienta de predicción sencilla y aplicable por profesionales de la construcción.

Palabras clave
modelo matemático, simulaciones, arquitectura sustentable

ABSTRACT

This work looks to build a predictive mathematical model that can provide a first approach to a building's energy requirement (ER) value in a temperate continental climate. The aim is to contribute to the theoretical knowledge of energy assessment tools. To do this, parametric simulations were run and processed using the EnergyPlus 9.5 and JePlus programs. The results were then used as a dataset to build different mathematical models, using the SageMath program to run equations that predicted the ER of each scenario. Work was done with the models, scaling their complexity with the methods and the number of parameters used. Finally, a model with a low error (0.08) and 15 parameters was chosen. It was noted that, although increasing the number of parameters brought the models closer to a 0.02 error, there was a risk of overfitting. The chosen model seeks to incorporate dynamic simulations' accuracy and validity into a simple prediction tool that construction professionals can apply.

Keywords
mathematical modeling, simulations, sustainable architecture

RESUMO

O objetivo deste trabalho é desenvolver um modelo matemático preditivo que possibilite uma primeira abordagem do valor dos requisitos de energia (ER) de um edifício em um clima continental temperado, de forma a contribuir para o conhecimento teórico das ferramentas de avaliação energética. As simulações paramétricas foram realizadas e processadas com os softwares EnergyPlus 9.5 e JePlus. Os resultados foram utilizados como Dataset para a construção de diferentes modelos matemáticos, para os quais foi utilizado o programa SageMath para desenvolver equações que preveem o ER de cada cenário. Trabalhamos com modelos que escalonam sua complexidade em termos de métodos utilizados e número de parâmetros. Foi selecionado um modelo com baixo nível de erro (0,08) e 15 parâmetros. Observou-se que, embora o aumento do número de parâmetros tenha aproximado os modelos ao erro de 0,02, havia o risco de sobreajuste. O modelo selecionado busca incorporar a precisão e a validade das simulações dinâmicas em uma ferramenta de previsão simples que pode ser aplicada por profissionais da construção.

Palavras-chave:
modelo matemático, simulações, arquitetura sustentável.

INTRODUCTION

The construction sector contributes significantly to global energy demand. The energy intensity of buildings has stayed the same in recent years, remaining at 150kWh/m^2. According to the estimates of the International Energy Agency (IEA), to achieve "net zero emissions," it is necessary that the intensity decreases by approximately 35% compared to current levels and remains around 95 kWh/m^2 (International Energy Agency, 2022). Unfortunately, this has remained virtually unchanged since 2019 (United Nations Environment Programme, 2022).

As the global population continues to grow, an increase in the energy demand from buildings is expected. One strategy to mitigate this situation is optimizing their energy efficiency, which can be addressed in their design, construction, and operation stages. Therefore, it is essential to have accurate forecasts of energy requirements, as it is becoming crucial to achieve significant energy savings in the construction sector (Chang et al., 2019).

Timuçin and Wilde (2021) warn that, when designing, more attention should be paid to the holistic investigation of all factors to achieve energy efficiency. To make this possible, it is necessary to consider a series of variables that influence energy consumption and user comfort, such as building orientation, envelope thermal quality, the relationship between opaque and translucent surfaces, and building shape.

Nowadays, professionals frequently resort to computational modeling and simulation (BPS or Building Performance Simulation) to evaluate and analyze different design and operation strategies. This is because the effectiveness of BPS has been documented in the literature and has been used in a wide range of applications (Azar et al., 2021; Raj et al., 2021; Schwartz & Raslan, 2013).

Both modeling and computational simulation are done before the construction or remodeling of a building, considering the variables mentioned above and the outdoor climatic conditions. The results obtained through this process are sufficient and accurate throughout a period and at the same frequency. These results can be the building's energy consumption, maximum loads, and indoor environmental conditions, among others (Seyedzadeh et al., 2019). However, this methodology usually requires many tests and lengthy periods (Papadopoulos et al., 2018) and demands a high level of expertise with powerful computing resources (Catalina et al., 2013). To overcome these limitations, researchers have begun to apply surrogate models that complement the capabilities of BPS. The process consists of training a mathematical model that mimics its performance and testing different building configurations at a low computational cost (Ye et al., 2019; Fang & Cho, 2019).

Substitute models allow users to predict the energy behavior of a building under different conditions. Some of the works that have used mathematical models to predict energy consumption include, for example, the use of neural network models or multiple linear regression models (Chou & Ngo, 2016; González-Vidal et al., 2017; Huang et al., 2021; Jiwon et al., 2022; Kwak et al., 2013; Zhao & Magoulès 2012). However, these are difficult for construction professionals to solve and access.

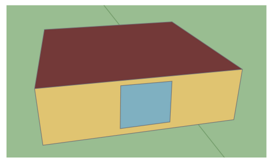
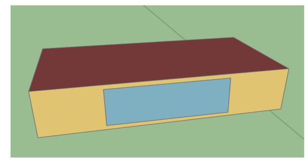
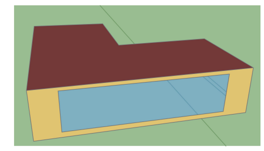
In this regard, this work aims to contribute to theoretical knowledge about energy assessment tools where it is unnecessary to resort to compelling but complex simulation environments. For this reason, the formulation of a simplified mathematical model based on simple morphological variables is proposed to predictively calculate the annual energy requirement for a building's air conditioning (REC). The argument is that simplifying mathematical models for initial energy assessments in buildings is currently subject to stationary thermal-energy balances, implying a gap between dynamic realities and the answers the BPS can provide. Due to this, the model sought aims to capture the variability of the thermal-energy-dynamic balance using the *EnergyPlus* program, given that the Dataset is built with the parametric simulations this makes. This simplified approach can offer construction professionals a practical and accessible tool for making energy-efficiency decisions.

Finally, it should be noted that the context where this model will be applied will be in buildings located in a temperate continental climate environment, specifically in the Mendoza region, Argentina.

METHODOLOGY

The study's work method is applied and divided into three sequential stages: the first is the parametric simulation, the second is creating the Dataset, and

Table 1. Variables considered for the study. Source: Preparation by the authors.

Discrete variable			
	C - square	R - rectangular	L - corner shape
Shape typology			
	Continuous variables		
v- WWR Factor (opaque openings and wall ratio)	20 - 30 - 40 - 50 – 60 – 70 – 80 – 90 - 100		
w- orientation	0 – 15 – 30 – 45 – 60 – 75 – 90 – 105 – 120 – 135 – 150 – 165 – 180 – 195 – 210 -225 – 240 – 255 – 270 – 285 – 300 – 315 – 330 – 345 – 360		
x-Wall - EPS insulation thickness (expanded polystyrene)	0.01 – 0.02 – 0.03 – 0.04 – 0.05 - 0.06 - 0.07 – 0.08 – 0.09 – 0.10 – 0.11 - 0.12 – 0.13 – 0.14 – 0.15 - 0.16 - 0.17 – 0.18 – 0.19 – 0.20		
y-Roof - EPS insulation thickness	0.01 – 0.02 – 0.03 – 0.04 – 0.05 - 0.06 - 0.07 – 0.08 – 0.09 – 0.10 – 0.11 - 0.12 – 0.13 – 0.14 – 0.15 - 0.16 - 0.17 – 0.18 – 0.19 – 0.20		

the third covers constructing the mathematical models.

Each of these consists of sub-stages, which are detailed below. The first parametric simulation stage is based on identifying the entry variables and their ranges to be used as inputs in the simulation model; the second is performing the parametric simulations for the climate of the city of Mendoza, establishing the data of air-conditioning energy requirements as an output.

On the other hand, the sub-stages in the Dataset creation are from processing the data obtained in the simulations with the training data. Finally, once this stage is completed, the third mathematical model creation stage begins, namely their elaboration process. Each of the stages and sub-stages is explained in detail below.

PARAMETRIC SIMULATION

Nowadays, computer simulations have strict validation in the studies and analysis of light, thermal, and energy behaviors, among others, for building projects or already built buildings (Malkawi, 2004). Therefore, the simulation data are considered realistic of the REC values of the building forms used. The parametric simulation methodology allows the systematic combination of all the variables in the same simulation procedure, as it simplifies the actions of the simulator user to execute and program the interaction of the variables one by one in individual simulations.

VARIABLES AND RANGES

INPUTS, Input data of the simulation models

The following variables were used as study variables: the shape, the orientation, the opaque-transparent envelope ratio, and the transmittance values of walls and roofs. Table 1 presents the categorized variables, the ranges used, and their subsequent denomination in the mathematical models.

Variables are divided into discrete and continuous. As discrete variables, the building typologies of houses are determined considering their shape:

square, rectangular, and L, exemplifying different compactness indices (CI), 88.6%, 82.6%, and 75.5%, respectively.

PARAMETRIC COMPUTATIONAL SIMULATIONS

In this phase, the *EnergyPlus* 9.2 and *Jeplus* programs were used to make parametric simulations. The parametric methodology is an exhaustive method that allows evaluating the cross-combination and interrelation of numerous values of ranges entered as inputs, changing one at a time. This results in a total of 270,000 simulations.

The three formal building typologies were modeled. With these models, the parametric simulations were made by modifying the input variables of Table 1. The models worked with a single thermal zone of 80m^2. In the materialization, the traditional and mass construction system of the City of Mendoza was taken as a reference, using for walls: mass ceramic brick, plaster on both sides, and thermal insulation; and for roofs: lightened concrete slabs, mortar for slopes, asphalt membrane, and thermal insulation. The variability of the construction packages was worked on by modifying the thermal insulation thicknesses, using EPS (expanded polystyrene) in both cases.

As an output, the Zone Ideal Loads Heating Energy and Zone Ideal Loads Cooling Energy outputs of the *EnergyPlus* program were used, which provide the heating and cooling energy requirement values. These values are added together to obtain the annual air conditioning total. Using this, thermostats related to the Olgyay comfort ranges were established, i.e., for winter, it was set at 20°C, and for summer, 24°C. The ideal load RECs were used, so specific HVAC systems were not considered.

CONSTRUCTION OF THE DATASET

To set up the Dataset, the results of the simulations of the previous stage were used, whose data were used to train the mathematical models. Unlike what is done with artificial neural network methodologies, in this study, to optimize the models and lower error values, the sample was not divided into a training group and a testing group, as obtaining more data would lead to an increase in the training sample.

The Dataset consists of two columns. The first has the case code name that represents the change of the value of each variable to combine the differences *one at a time* among all of them. The second column has the REC value obtained by the simulation. The outline built is presented in Table 2.

Table 2. Dataset outline built from parametric simulations. Source: Preparation by the authors based on the results.

CASE NAME	REC VALUE [Kw]
EP_G_Pv_0_Pw_0_Px_0_Py_0	x1
EP_G_ Pv_0_Pw_0_Px_0_Py_1	x2
EP_G_ Pv_0_Pw_0_Px_0_Py_2	x3
EP_G_ Pv_0_Pw_0_Px_0_Py_nx	xN
EP_G_ Pv_1_Pw_3_Px_7_Py_0	x5
EP_G_ Pv_1_Pw_3_Px_7_Py_1	x6
EP_G_ Pv_1_Pw_3_Px_7_Py_2	x7
EP_G_ Pv_ nx _Pw_ nx _Px_ nx _Py_ nx	xN

Where:
EP: EnergyPlus;
G: Climate file;
Pv: WRR Variable;
Pw: Orientation variable;
Px: WALL insulation thickness variable;
Py: ROOF insulation thickness variable;
Nx: number of times q changes the value of the range of each variable until the combination of all of them is completed, in this case, the 270,000 cases;
x1-x2-xN: REC values obtained from the simulations for each case.

CONSTRUCTION OF MATHEMATICAL MODELS

Development of mathematical models

Once the Dataset outline stage is over, the third mathematical model development stage begins. For this, the information synthesized in the Dataset was input into the *SageMath* software, whose role is to build mathematical models. In the process, a balance was sought between obtaining a fine model and the statistical model that approached the reference value, which was taken from the results obtained from the simulations (REC). In this way, each mathematical model was developed as an equation where the independent variables are the continuous variables (v: WWR factor, w: orientation, x: Wall-EPS insulation thickness, y: Roof-EPS insulation thickness). The least squares fit sets the parameters of the equations using computational simulations. Once the parameters have been determined in the equation, it can be used to predict the building's REC by replacing the continuous variables with the value of the building in question.

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Table 3. Types of models tested and fit measures for each. Source: Preparation by the authors

MODELS	ERROR MEASUREMENTS								
	Square shape			Rectangular shape			L-shape		
	Min.	Max.	STD	Min.	Max.	STD	Min.	Max.	STD
L	-0.123	0.127	0.047	-0.213	0.296	0.099	-0.26	0.224	0.083
Lin	-0.89	0.097	0.033	-0.121	0.219	0.06	-0.199	0.153	0.062
CC/C	0.05	0.064	0.018	-0.094	0.126	0.042	-0.078	0.116	0.033
Cs/C	-0.081	0.116	0.035	-0.154	0.177	0.053	-0.183	0.211	0.063
CIn c/C	-0.044	0.037	0.009	-0.063	0.067	0.022	-0.046	0.061	0.016
CIn s/C	-0.081	0.107	0.032	-0.136	0.154	0.042	-0.17	0.196	0.059
CIn c/R	-0.07	0.056	0.018	-0.086	0.093	0.032	-0.071	0.071	0.023
CIn c/r2	-0.067	0.058	0.018	-0.077	0.095	0.031	-0.074	0.063	0.023
F2t	-0.038	0.031	0.013	-0.101	0.168	0.058	-0.05	0.076	0.022
F3t	-0.03	0.23	0.011	-0.048	0.044	0.018	-0.029	0.053	0.011
F3t/S	-0.036	0.028	0.012	-0.069	0.062	0.032	-0.039	0.061	0.015
F4t	-0.026	0.02	0.006	-0.052	0.015	0.007	-0.028	0.047	0.008

A total of 40 mathematical models were made, trying not to make them unnecessarily complicated. An exploration of options was carried out that began with linear models, which yielded high errors of around 29.6%. For reference, the more parameters a model has, the fewer errors it should have. However, this can be risky if "overfitting" is produced. To avoid this, models with errors that did not decrease substantially by increasing the number of parameters were preferred. Consequently, the improvements were made with quadratic models. In addition, orientation was highlighted as an angular variable, which led to the need to upgrade to trigonometric models.

RESULTS

Different results obtained from the models that allowed an approximation to a simple generic equation were explored. These were analyzed in two senses: one, the equation, its form and development in terms of quantity and representativeness of the parameters involved, and the other, from the error as a diagnostic object of the predictive value and the effectiveness of the model.

Evaluating the relative minimum and maximum errors was considered a goodness-of-fit measure. The tested models and the error measurements compared to each shape are presented in Table 3. The standard deviation value is also presented as a goodness-of-fit measure.

CC/C Quadratic with cross-terms
Cs/C Quadratic without cross-terms
L Linear
CInc/C Inverse quadratic with cross-terms
CIns/C Inverse quadratic without cross-terms
Lin Inverse linear
F4t Fourier 4 terms □ looks like overfitting
F3t Fourier 3 terms
F3t/S Fourier 3 symmetric terms
F2t Fourier 2 terms
CIn c/R Inverse quadratic with clipping
CIn c/R^2 Inverse quadratic with clipping V2

The models were divided by family, linked to the assumed hypotheses. Of the 40 models explored, three stand out due to the following reasons:

a. The errors in the predictions obtained are limited;
b. The number of parameters does not lead to overfitting and
c. They allow for analyzing energy consumption behavior regarding the included variables.

The three models that were considered optimal are presented below:

Model 1 [M1] (model 01, Linear Fourier 2 even terms) (Equation 1)

$$Co(v,w,x,y) = F + F_v v + F_x \frac{1}{x} + F_y \frac{1}{y} \qquad \text{(Equation 1)}$$

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Where:

$$F_i = A_i + B_i cos\left(\frac{\pi}{180}w\right)$$

This model has 8 parameters (A, B, Av, BV, Ax, Bx, Ay, and By). The values estimated for each shape are presented in Table 4.

Table 4. Values of the estimates for the parameters of Model 1. Source: Preparation by the authors.

Model 1	C	L	R
A	10633.1	2190.61	5093.01
B	-128.62	-250.7	-442.29
Av	-17.49	-4.49	-5.33
Bv	-14.67	-6.56	-12.09
Ax	14.76	10.7	12.97
Bx	1.79	1.49	2.34
Ay	2.09	4.97	3.9
By	5.94	1.96	3.75

Model 2 [M2] (quadratic angular model 30 even terms) (Equation 2)

$$Co(v,w,x,y) = F + F_w cos\left(\frac{\pi}{180}w\right) + F_v v + F_x \frac{1}{x} + F_y \frac{1}{y}$$
$$+F_{ww} cos^2\left(\frac{\pi}{180}w\right) + F_{vv} v^2 + F_{xx}\frac{1}{x^2} + F_{yy}\frac{1}{y^2}$$
$$+F_{wv} v cos\left(\frac{\pi}{180}w\right) + F_{wx} cos\left(\frac{\pi}{180}w\right)\frac{1}{x} + F_{wy} cos\left(\frac{\pi}{180}w\right)\frac{1}{y}$$
$$+F_{vx} v\frac{1}{x} + F_{vy} v\frac{1}{y} + F_{xy}\frac{1}{xy} \quad \text{(Equation 2)}$$

This model uses 15 parameters. The fit values thereof are presented in Table 5.

Table 5. Values of the estimates of the parameters of the Model 2. Source: Preparation by the authors.

Model 2	C	L	R
F	11226.94	2459.96	5834.87
Fw	-128.62	-250.7	-442.29
Fv	-35.09	-14.09	-29.29
Fx	5.28	8.44	6.76
Fy	-6.28	4.61	2.91
Fww	40.69	-8.89	-148.99
Fvv	0.11	0.06	0.17
Fxx	-0.02	-0.03	-0.05
Fyy	0.01	-0.03	-0.04
Fwv	-14.67	-6.56	-12.09
Fwx	1.79	1.49	2.34
Fwy	5.94	1.96	3.75
Fvx	0.16	0.07	0.17
Fvy	0.09	0.04	0.06
Fxy	0.12	0.07	0.05

Model 3 [M3] (model 15, Quadratic Fourier, 2 even terms) (Equation 3)

$$Co(v,w,x,y) = F + F_v v + F_x \frac{1}{x} + F_y \frac{1}{y}$$
$$+F_{vv} v^2 + F_{xx}\frac{1}{x^2} + F_{yy}\frac{1}{y^2} + F_{vx}\frac{v}{x} + F_{vy}\frac{v}{y} + F_{xy}\frac{v}{xy}$$

(Equation 3)

Where (Equation 4):

$$F_i = A_i + B_i cos\left(\frac{\pi}{180}w\right) \quad \text{(Equation 4)}$$

The values of the parameters are presented in Table 6. In this case, a total of 20 is used.

Table 6. Values of the estimates of Model 3's parameters
Source: Preparation by the authors.

Model 3	C	L	R
A	11247.28	2455.51	5760.38
B	-197.85	-105.05	-16.54
Av	-35.09	-14.09	-29.29
Bv	-13.03	-13.39	-29.96
Ax	5.28	8.44	6.76
Bx	2.33	2.29	2.32
Ay	-6.28	4.61	2.91
By	8.97	3.49	5.35
Avv	0.11	0.06	0.17
Bvv	-0.03	0.05	0.14
Axx	-0.02	-0.03	-0.05
Bxx	-0.02	-0.01	-0.01
Ayy	0.01	-0.03	-0.04
Byy	-0.07	-0.02	-0.04
Avx	0.16	0.07	0.17
Bvx	0.03	0.01	0.03
Avy	0.09	0.04	0.06
Bvy	0.07	0.02	0.04
Axy	0.12	0.07	0.05
Bxy	-0.01	-0.01	-0.01

Table 7. Min, Max, and Std absolute and relative error measurements for the square shape. Source: Preparation by the authors.

S-Shape	Absolute errors			Relative errors		
	Min	Max	Std	Min	Max	Std
M1	-1693	726	183	-0.14	0.07	0.02
M2	-801	897	125	-0.06	0.08	0.01
M3	-521	899	118	-0.05	0.08	0.01

Table 8. Min, Max, and Std absolute and relative error measurements for the rectangle shape. Source: Preparation by the authors.

R-Shape	Absolute errors			Relative errors		
	Min	Max	Std	Min	Max	Std
M1	-1304	735	189	-0.19	0.17	0.04
M2	-551	1038	110	-0.08	0.14	0.02
M3	-597	980	104	-0.09	0.18	0.02

Table 9. Min, Max, and Std absolute and relative error measurements for the corner shape. Source: Preparation by the authors.

L-Shape	Absolute errors			Relative errors		
	Min	Max	Std	Min	Max	Std
M1	-875	352	103	-0.21	0.17	0.05
M2	-362	564	72	-0.16	0.14	0.04
M3	-347	538	67	-0.14	0.14	0.03

The predictive value of each model, the absolute minimum and maximum errors, relative errors, and the standard deviation (Std) between the mathematical model and the prediction of the simulations are presented in Table 7 for the S-shape and Tables 8 and Table 9 for L and R.

These analyses show that, in the S-Shape with the M2, the REC value calculated by the model may have a relative error of 1.2%. The minimum and maximum error values are the percentage of error that can occur when the model's equation gives a lower (Min error) or a higher consumption (Max error) compared to the reference. Following the example of M2, the error can vary by 6%, giving a lower value of REC, and by 8%, giving a higher value of REC.

USE OF THE MODEL IN A DESIGN EXAMPLE

For the following example, a housing project with the characteristics presented in Table 12 was assumed.

Table 10. First variables assumed for a housing project, Case n. Source: Preparation by the authors.

Shape	Square	Rectangular	L
v -WWR	40%	40%	40%
w - orientation	0 (North)	0 (North)	0 (North)
x – wall insulation thickness	0.01 (considering a wall without insulation)	0.01 (considering a wall without insulation)	0.01 (considering a wall without insulation)
y – roof insulation thickness	0.05	0.05	0.05

The REC is obtained with the variables of Table 10 and using Model 1 (considering it as optimal). For this, the first step is to obtain the values of F (Equation 5), Fv (Equation 6), Fx (Equation 7), and Fy (Equation 8) for w=0:

$$F = A + B\cos\left(\frac{\pi}{180}w\right) = 2190.6 - 250.7\cos\left(\frac{\pi}{180}0\right) = 1939.9 \quad \text{(Equation 5)}$$

$$F_v = A_v + B_v\cos\left(\frac{\pi}{180}w\right) = -4.49 - 6.56\cos\left(\frac{\pi}{180}0\right) = -11.05 \quad \text{(Equation 6)}$$

$$F_x = A_x + B_x\cos\left(\frac{\pi}{180}w\right) = 10.7 + 1.49\cos\left(\frac{\pi}{180}0\right) = 12.19 \quad \text{(Equation 7)}$$

$$F_x = A_x + B_x\cos\left(\frac{\pi}{180}w\right) = 10.7 + 1.49\cos\left(\frac{\pi}{180}0\right) = 12.19 \quad \text{(Equation 8)}$$

With these values, this is replaced in the model's equation (Equation 9):

$$Co(v,w,x,y) = F + F_v v + F_x\frac{1}{x} + F_y\frac{1}{y} = 1939.9 - 11.05 \times 40 + 12.19\frac{1}{0.01} + 6.93\frac{1}{0.05} = 2855.5$$

(Equation 9)

The values obtained with the mathematical models are compared with the results of the simulations' Dataset to evaluate the margin of error. These values are presented in Table 11, where it is observed that the errors are within the thresholds presented in Table 7, Table 8, and Table 9, where the Max for the square shape is 7% and 17% for the rectangular and L shapes.

Table 11. Results of the air conditioning energy requirement [KW/m2] and relative error. Source: Preparation by the authors.

	Original Square	Original Rectangle	Original L
	Original	Original	Original
Mathematical model	11034	5638	2855
Computational simulation	10646.97	5067.73	2656.52
Relative error	4%	11%	8%

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Table 12. Variables corrected to improve the Case n project. Source: Preparation by the authors.

Shape	Square	Rectangular	L
v -WWR	20%	30%	30%
w - orientation	0 (North)	0 (North)	0 (North)
x - wall insulation thickness	0.05	0.05	0.1
y - roof insulation thickness	0.1	0.1	0.1

Table 13. Results of the air conditioning energy requirement [KW/m2] and energy saving percentage. Source: Preparation by the authors.

	Square		Rectangular		L	
	Original	Improved	Original	Improved	Original	Improved
Mathematical model result	11034	10273	5638	4510	2855	1800
REC Reduction		7%		20%		37 %

The values allow considering changes and improvements in the project, such as increasing insulation in walls and ceilings, leading to the values of x=0.1 and y=0.1, and reducing the proportion of openings to 20% in the S shape and 30% in the R and L shapes. (Table 12).

When calculating with the mathematical model, improvements in reducing the energy requirement are observed. These results are presented in Table 13.

Energy reduction and savings are differentiated between building shapes. Up to 37% improvement is achieved in the L shape, 20% for the rectangular shape, and less than 7% for the square shape. This allows differentiating improvement and bioclimatic design strategies for the building's different geometric configurations. In addition, it reveals the importance and potential of the mathematical models.

DISCUSSION

Mathematical modeling is advantageous for predicting the REC. Although using 20 parameters may seem excessive, this contrasts with the time, resources, and expertise needed to perform the 270,000 simulations that fed the model.

In the error analysis, the restricted relative error below 2.1% is considered acceptable. Regarding the number of parameters, a substantial improvement is obtained by moving from M1 (8 parameters) to M2 (15 parameters). However, when moving from M2 to M3 (20 parameters), the same relevance is not observed in the model's improvement, so it can be noted that considering models with more than 20 parameters does not have predictive advantages and runs the risk of overfitting.

As for the models not presented, it is important to emphasize that choosing the model's functional shape strongly affects predictive ability. That is, instead of considering 1/x and 1/y as variables, x and y will be taken into account directly, and the errors grow substantially. The same occurs for the angular dependence in *w*. A "*goodness of fit*" measurement is also made for all models on the calculated values, using the ***chi-square over degrees of freedom*** ***(x^2/d.o.f.)*** methodology. This allows evaluating whether the errors are randomly distributed compared to the prediction, in terms that, if the model fits well, the value of x^2/dof should be the closest to 1.

Table 14 shows models that deviate considerably from the reference measurement (1) and others that are reasonable, although they are not perfect. However, since the Dataset is very numerous and the parameters are few, one can opt for the path of making more models with a greater number of parameters and, in this way, ameliorate the x^2/dof. The problem is that the models become more complex, losing their simplicity.

The improvement observed in moving from model 1 to model 2 shows that switching to non-linear

Table 14. Chi-square over degrees of freedom values. Source: Preparation by the authors.

Model	No of Parameters	Shape		
		C	L	R
01 Linear Fourier 2 even terms [M1]	8	3.4	5	7.4
02 Linear Fourier 2 odd terms	8	51.6	93.5	130.4
03 Linear Fourier 3 terms	12	3.2	5	7.2
04 Linear Fourier 3 even terms	12	3.3.	4.5	6.3
05 Linear Fourier 3 odd terms	12	51.6	93.3	130.4
06 Linear Fourier 4 terms	16	3.2	4.8	6.1
07 Linear Fourier 5 terms	20	3.2	4.3	6.1
08 Fourier Quad STC 2 even terms	14	2.8	3.4	6.1
09 Fourier Quad STC 2 odd terms	14	51.1	92.6	128,5
10 Fourier Quad STC 3 terms	21	2.7	3.4	3.9
11 Fourier Quad STC 3 even terms	21	2.7	3.4	3.9
12 Fourier Quad STC 3 odd terms	21	51	92.4	128.4
13 Fourier Quad STC 4 terms	28	2.6	3.1	2.7
14 Fourier Cuad STC 5 terms	35	2.6	2.7	2.7
15 Fourier Quad 2 even terms [M3]	20	1.4	2.2.	2.1
16 Fourier Quad 2 odd terms	20	1.4	2.2	2.1
17 Fourier Quad 3 terms	30	1.3	2.1	1.9
18 Fourier Quad 3 even terms	30	1.3	1.7	0.9
19 Fourier Quad 3 odd terms	30	49.8	91.4	126.9
20 Fourier Quad 4 terms	40	1.2	1.8	0.7
21 Fourier Quad 5 terms	50	1.2	1.4	0.7
22 Fourier Linear Extra 2 even terms	12	3.3	4.8	7.2
23 Fourier Linear Extra 2 odd terms	12	51.6	93.4	130.3
24 Fourier QuadExtra V1 2 even terms	20	1.4	2.4	2.9
25 Fourier QuadExtra V1 2 even terms	20	49.8	91.7	127.5
26 Fourier Quad lExtra V2 2 even terms	20	1.4	2.4	2.2
27 Fourier Quad Linear Extra V2 2 odd terms	20	49.9	91.8	127
28 Angular Quad STC even	9	11.2	11.5	15.5
29 Angular Quad STC odd	9	51	92.7	129.1
30 Angular Quad even [M2]	15	1.6	2.5	2.4
31 Angular Quad odd	15	49.8	91.7	127.4
35 Linear	5	56.8	58.4	135.6
36 Quadratic STC	9	16	49.4	24.2
37 Quadratic	15	14.5	44.5	22.2
38 Inverse linear	5	51.5	45.9	129.1
39 Inverse quadratic STC	9	13.9	45.1	21.5
40 Inverse quadratic	15	12.6	40.2	18.9

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models is the right decision. However, it is necessary to emphasize that achieving reasonable predictions with the consequently less complex linear models is feasible. The use of non-linear models allows conclusions to be reached regarding the importance of the different variables, not only by themselves but also in synergy with the others. M2 is chosen to discuss this point. This seems to be the most successful model of the search carried out in this work.

The standardized M2 parameters, similar to those presented in Table 5, are presented in Table 15, considering the range of the associated variable. That is to say, the change that this variable produces in consumption when it passes from one end of its range to the other makes it possible to see the importance of each term in the REC clearly.

Table 15. Values of the estimates of Model 2's parameters. Source: Preparation by the authors.

Model 2	C	L	R
F	11227	2460	5835
Fw	-257	-501	-885
Fv	-3509	-1409	-2929
Fx	528	844	676
Fy	-628	461	291
Fww	41	-9	-149
Fvv	1099	631	1660
Fxx	-215	-350	-474
Fyy	89	-328	-358
Fwv	-2934	-1312	-2418
Fwx	357	298	468
Fwy	1188	391	750
Fvx	1560	740	1653
Fvy	887	389	596
Fxy	1217	662	477

The first thing observed is that a high degree of consumption is given by parameter F, namely the constant in the model that does not depend on any of the variables. It is also important that the lowest constant is obtained for the L-shape, which highlights that architectural design substantially impacts energy consumption. On this consumption basis, the angular dependence given by *Fw* and *Fww* is not substantial.

Remembering what happens with Fv, whose role contributes to the glazed surface proportion, is also necessary. This term is always important and, moreover, negative, indicating that an increase in the glazed surface leads to reduced consumption. However, it is noted that *Fvv* (glazed surface), in the quadratic term, leads to an increase in consumption, although considerably less than the savings if the term were linear.

Finally, analyzing individual variables shows that the roof and wall insulation thickness have a lower impact than other variables. This means that there is a minor impact on consumption. The most important crossover term is *Fwv*, which, moreover, is negative. The rest of the terms are of intermediate importance, which shows that, although there are factors to highlight, an oversimplification of the model and design considerations is detrimental.

CONCLUSIONS

This research addresses the study of representative equations to obtain the housing's REC value. When making constructive decisions, the energy requirement is one of several factors to consider. Within this analysis, having a predictive model such as this one simplifies decision-making, allowing decisions to be made on quantitative considerations.

Forty mathematical models were run based on the results of parametric simulations, with non-linear models considered more suitable for balancing complexity for non-specialist users with low error levels.

The models considered optimal showed that it is possible to approach a reference value simply. The case used to demonstrate this serves to verify the values using the simulations, considering these as plausible. The results show that these models correctly fit a first analysis and are the basis for accurate energy-efficient decisions in the first steps of the architectural project.

This work can be replicated in other regions of the country by changing the climate archive. The work comprises a diversity of total transmittance values of different walls and roofs, orientations, and WWR ratios. For future work, it is felt that it is both necessary and possible to reduce the data used as a Dataset by using sampling and categorization methodologies such as LHS (Latin Hyper Cube).

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EVALUATING ACCESSIBILITY TO UNDERGROUND TRANSPORT SYSTEMS: ANALYSIS OF THE SANTIAGO - CHILE METRO

EVALUACIÓN DE LA ACCESIBILIDAD PARA SISTEMAS DE TRANSPORTE SUBTERRÁNEO: ANÁLISIS DEL METRO DE SANTIAGO - CHILE

AVALIAÇÃO DE ACESSIBILIDADE PARA SISTEMAS DE TRANSPORTE SUBTERRÂNEO: ANÁLISE DO METRÔ DE SANTIAGO DO CHILE

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RESUMEN

Considerando que una parte importante de la población mundial vive con algún tipo de discapacidad y que la esperanza de vida aumenta, el hecho de tener un transporte accesible permitiría que las personas mejoraran su calidad de vida, accediendo a más oportunidades socioeconómicas. A partir de un diseño descriptivo mixto (cualitativo etnográfico y cuantitativo), este artículo presenta una herramienta de evaluación del nivel de accesibilidad en el uso del tren subterráneo para personas con discapacidad visual, física, cognitiva y auditiva. Se analizaron los datos de 30 estaciones del Metro de Santiago de Chile, estudiando el desplazamiento desde el exterior a la estación, la permanencia en zona de pagos y el desplazamiento hacia andenes y combinaciones. De los indicadores evaluados, los que tienen relación con el desplazamiento hacia el andén son los que presentan menores niveles de accesibilidad, ya que no responden a todas las necesidades para los distintos tipos de discapacidad analizados.

Palabras clave
discapacidad sensorial, discapacidad física, discapacidad cognitiva, metro, accesibilidad

ABSTRACT

Considering that a significant part of the world's population lives with some disability and life expectancy is increasing, accessible transportation would allow people to improve their quality of life and access more socioeconomic opportunities. Based on a mixed descriptive design (qualitative, ethnographic, and quantitative), this article presents a tool for evaluating the level of accessibility to subway trains for people with visual, physical, cognitive, and hearing disabilities. Data from 30 Metro stations in Santiago de Chile were analyzed, studying movements into the station, permanence in the payment area, and movements toward platforms and connecting lines. Among the indicators evaluated, those related to getting to the platform have the lowest levels of accessibility, as they do not meet all the needs of the different types of disabilities analyzed.

Keywords
sensory impairment, physical disability, intellectual disability, subway, accessibility

RESUMO

Considerando que uma parte significativa da população mundial vive com algum tipo de deficiência e que a expectativa de vida está aumentando, dispor de um transporte acessível permitiria que as pessoas melhorassem sua qualidade de vida, tendo acesso a mais oportunidades socioeconômicas. Com base em um projeto descritivo misto (qualitativo, etnográfico e quantitativo), este artigo apresenta uma ferramenta de avaliação do nível de acessibilidade no uso do metrô para pessoas com deficiências visuais, físicas, cognitivas e auditivas. Foram analisados dados de 30 estações de metrô de Santiago do Chile, estudando o deslocamento do exterior ao interior da estação, o tempo de permanência na área de pagamento e o deslocamento para as plataformas e combinações. Dos indicadores avaliados, os relacionados ao deslocamento até a plataforma são os que apresentam os níveis mais baixos de acessibilidade, pois não atendem a todas as necessidades dos diferentes tipos de deficiência analisados.

Palavras-chave:
deficiência sensorial, deficiência física, deficiência cognitiva, metrô, acessibilidade.

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INTRODUCTION

According to World Health Organization (WHO) data, 16% of the world's population has a disability (World Health Organization, 2023). Of this figure, about 85 million people are in Latin America. In 2022, the over-60s in the region represented 13.4%, and projections indicate that this number could increase to 25.1% in 2050 (ECLAC, 2022). The relationship between both statistics is relevant because the prevalence of disability increases with age.

This also affects urban development and, more specifically, transport, as older people with difficulties getting around and people with disabilities (hereinafter, PWD) often only have access to public transportation to get around, or this is their preferred option. It is for this reason that it becomes essential to evaluate both the needs of the population regarding infrastructure in each country and the importance of the spatial position between public infrastructure and housing, as this leads to the development of PWD's socio-economic opportunities (Lima et al., 2019; Sze & Christensen, 2017).

There are different studies on the phenomenon of accessibility in urban areas. Some analyze accessibility to a place, as well as the effective way to help people get to their destination (Jiron & Mancilla, 2013); others have studied satisfaction with travel (Lättman et al., 2019; Grisé et al., 2019; Wong, 2018); or with the different forms of transport (Wong et al., 2017; Bascom & Christensen, 2017).

On the other hand, the topic of study of this work is the research of Srichuae et al. (2016), who investigate the factors that affect the mobility of older people, such as the distribution of public spaces with accessible transport services and the ability to travel unassisted, highlighting the need to include universal design principles. Cochran (2020) analyzes the experiences of PWD when using transportation, pointing out that there needs to be more analysis of travel behavior as it represents one of the barriers to using transportation. Sze and Christensen (2017) review accessible transport design guidelines in the EU, UK, and Hong Kong that could affect travel behavior, activity patterns, and choice of transport for PWD, emphasizing that accessible design should be implemented in a more integrated transport network approach.

In Chile, different authors (Jirón & Mancilla, 2013; Vecchio et al., 2020) have addressed diverse research approaches to understand social exclusion from urban everyday mobility. Within these is the study of accessibility, which includes the physical-spatial conditions or how barriers can be understood from their spatiality as those limitations that subjects encounter daily in their movements through the city.

Concerning accessibility and mobility, the work of Kaufmann et al. (2004) redefines accessibility as a structuring dimension of social life, far from simply being a connection between points. "Motility," which encompasses socio-spatial mobility, is an asset that varies between individuals, groups, and institutions in access, competition, and appropriation. This approach highlights the complexity of relationships between social and territorial structures, connecting accessibility with the ability to access and appropriate goods, information, and people in different local and geopolitical contexts.

In this way, accessibility, within the framework of motility, becomes a critical component for understanding the dynamics of highly mobile societies. In the case of Cass et al. (2005), it is emphasized that the notion of accessibility is complex and goes beyond describing the exclusion of social groups from specific services, as it focuses on spatial awareness and is related to the mobility of citizens. By linking the interconnected society with the dispersion of everyday life, the author identifies the growing "mobility burden" in society. In addition, the importance of considering the spatial and temporal dimensions of transport provision and the connection with social networks that people want to be a part of is underlined, highlighting the dynamics and importance of networks in social inclusion.

Continuing with the search for accessibility analysis, Lucas et al. (2016) propose using the ethical theories of egalitarianism and sufficiency as a theoretical framework to evaluate Spatial Accessibility Indices, highlighting the need to identify indicators and thresholds in collaboration with the parties involved, especially with people that have fallen further behind concerning this index.

In another aspect, the subway train or metro is an essential means of transport for urban mobility, and, therefore, it is necessary to review their accessibility. Most publications focus on reviewing and analyzing their characteristics based on an individual's ability to cover the distance between origin and destination (Bascom & Christensen, 2017), where the travel time (Márquez et al.,

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2019; Park et al., 2022; Wong, 2018), waiting time (Vandenbulcke et al., 2009) or walkable distances (Yun, 2019), are analyzed. Although Prasertsubpakij and Nitivattananon (2012) propose a 24-indicator evaluation method for the Bangkok metro, the study focuses on interviews that evaluate the satisfaction of a broad group of users. However, it does not include sensory or cognitive disability. Thus, the need for an exhaustive analysis of the place and the components that allow comparable access and use for people with diverse abilities is evidenced (Shen et al., 2023; WHO, 2023).

According to the WHO, disability exists when there is no adequate relationship between the environment and a person's functional abilities, and, therefore, there is a limitation in activities or restrictions to social participation (World Health Organization, 2023). Therefore, built environment barriers will cause PWD to experience reduced functional capacity. This group faces more barriers when traveling due to physical, sensory, and cognitive limitations, resulting in fewer trips, shorter routes, and longer travel times (Shen et al., 2023). Because of this, in America, more than 33% of the PWD choose not to travel (Brumbaugh, 2018). Considering that the PWD travel primarily for medical reasons (Krahn et al., 2015) and that the population is aging, it is necessary to reduce these barriers in infrastructure and transport so that a PWD can move freely and independently to any public or private space.

Thus, by focusing on spatial and physical barriers in transportation, a universal design that everyone can use to the greatest extent possible without needing any adaptation or specialized design is expected (Iwarsson & Stahl, 2003). For this, universal design is based on seven principles: equitable use, flexibility of use, simple and intuitive use, perceptible information, tolerance to error, low physical effort, and size and space of approach and use (Iwarsson & Stahl, 2003). To apply these principles, a universal design, unlike an accessible design that seeks to design only for the specific group with disabilities and thus generates exclusion (ISO, 2001), must integrate accessibility and usability features from the beginning, eliminating all preconceived ideas and embracing the social inclusion of the largest possible number of users, regardless of their condition.

Given the above, this article presents an assessment tool for the level of accessibility in the use of a subway for visual, physical, cognitive, and auditory PWD. This tool analyzed the data collected from 30 Santiago de Chile Metro System (SMS) stations, studying the displacement from the outside to the metro line, the time in the payment area, and the displacement to the platform.

METHODOLOGY

This study has a mixed qualitative-quantitative approach. From the point of view of its design, it is a sequential descriptive approach (Hernández Sampieri et al., 1997), with an initial qualitative ethnographic phase (Hammersley & Atkinson, 2007) that explores the accessibility needs in the Santiago de Chile Metro System for PWD, and a second quantitative phase that consists of determining an assessment system to report about the level of accessibility in the metro stations.

In the ethnographic phase, the consent of PWD using the Santiago de Chile Metro System was obtained to collect data through field participant observations, informal conversations, and semi-structured interviews (from people in wheelchairs, older people with displacement problems, blind people, and caregivers of older person with cognitive issues). This process was carried out over 64.5 hours between August and September 2021, where different stations of several lines of the Santiago de Chile Metro System were visited to obtain a broad and representative perspective. Audiovisual recordings of the stations were taken, and relevant architectural elements were measured, making tours with PWD. The data collected were systematized using tables of qualitative and quantitative indicators.

An ethnographic approach based on the compressed model proposed by Jeffrey and Troman (2004) was followed to ensure the naturalness of the observed behaviors. The data analysis at this stage was based on the Grounded Theory principles (Glaser & Strauss, 1967), which allowed organizing and analyzing information rigorously through coding techniques to generate interrelated categories and subcategories. The triangulation of the information obtained involved comparing data from several sources, reviewing information from other researchers, and contrasting the researchers' observations, which determined the validity of the information collected.

In the quantitative stage, an assessment methodology was designed based on the systematic literature review and previous qualitative findings. Evaluation indicators were identified (mainly focused on the spatial physical barriers), and parameters

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were assigned to determine the level of accessibility. To validate the methodology, the stations of Line 5 of the Santiago metro system were analyzed, considering the following characteristics:

- This is one of the three oldest lines in the system, so there are unresolved accessibility criteria.
- It is the system's longest line and has the highest number of stations (30 stations).
- The line runs through the most communes (10) with different socioeconomic strata.
- It has three types of construction systems: elevated, street level, and underground stations,
- It has the largest number of combinations with other lines and intermodal stations.
- It travels through strategic points, such as universities, clinics and hospitals, public spaces, and historical and commercial centers.

CASE STUDY

The Santiago public transport system incorporates all the public transport buses of the capital, Metro-Tren Nos (surface train line), and the Santiago de Chile Metro System. The latter is the axis of the system, one of the city's most important means of public transport. The Santiago de Chile metro system began to be structured during the 1960s and currently has six lines covering 142.4 km (Figure 1). In November 2017, when Line 6 began operating, an average of

Figure 1. Spatial and descriptive configuration with data on length, number of stations, number of communes served, % of the overall public using the Santiago de Chile Metro System lines, and location of the analyzed stations. Source: Preparation by the authors.

more than 85,000 people were transported per hour (Santiago Metro, 2020).

Since 2012, Metro S.A., the company that runs the metro system, has enacted an accessibility plan to adapt to current requirements. One of its objectives was to provide elevators to all the network's stations, completed in 2019 (Metro de Santiago, 2020). In addition, the remodeling included activating configurable two-way doors in stations, preferential spaces in cars for people in wheelchairs, communication devices between passengers and drivers, LED maps to indicate upcoming stations, and cameras inside the trains. This plan will allow PWD circulating on the network to have greater accessibility from their entry to the station until their exit.

RESULTS AND DISCUSSION

REVISION OF BARRIERS AND NEEDS

The PWD accompanied on their different routes through the Santiago Metro had the following types of disabilities:

1. visual, understood as those deficiencies, limitations, and restrictions that a person with an ocular disease faces when interacting with their physical, social, or attitudinal environment (Espinosa-Muñoz, 2016; Alarcón & Vizcarra, 2016; Shen et al., 2023);
2. physical, people who, for different reasons, have difficulty moving, either temporarily or permanently (Saéz-González, 2020; Olivares-Medina et al., 2019; Shen et al., 2023);
3. cognitive, which involves limitations of intellectual functioning, as well as adaptive behavior in the conceptual, social, and practical domains (Brusilovsky, 2014; CEAPAT, 2018); and
4. auditory, people who, when interacting with the environment, face barriers that prevent their access to auditory-oral information and communication given by the language (Espínola-Jiménez, 2015; Agudelo-Zapata & Cadavid-Ospina, 2016).

The barriers and needs encountered were described through a literature review and experiential tours where the interviewees reported on their assessments. They were later categorized according to the type of disability (Table 1). Some of these assessments served as the basis for creating the evaluation indicators.

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Table 1. Disabilities – Barriers. Source: Preparation by the authors.

Visual Disability	Physical Disability	Cognitive Disability	Auditory Disability
Lack of tactile guides	Lack of escalators or not operational.	Lack of contrast on the elevator buttons.	Lack of visual information inside trains regarding the location and upcoming stations
Lack of tactile warning at the beginning and end of stairs and platform	Height and diameter difference in handrails	User support people with no training in disability	Lack of information through screens in elevators
Horizontal difference between the car and the platform	Lack of a preferential window.	Lack of suitable information for cognitive PWD when faults occur in the subway.	Lack of lighting information on some trains when there are service outages or station closures.
Lack of auditory information in elevators.	Lack of configurable two-way doors	Poorly located signs, with little or no lighting.	Lack of timely information on platforms due to failures in information monitors.
Lack of adequate lighting at some points.	Height of elevator buttons out of reach for People in Wheelchairs (PiW)	Information mural with incomprehensible symbology for cognitive PWD	Lack of information on trains about the status of elevators at certain stations
Lack of tactile guide at the entrance, ticket office, elevators, and stairs.	Height of information murals not accessible for PiW	Confusing digital information (Metro line- weather and advertising) - some turned off.	
Lack of tactile guide at the entrance, ticket office, elevators, and stairs.	Vertical difference between the car and platform.		
Lack of vending or rail-card charging machines with Braille or audio system	Platform seats at inappropriate height.		
	Ramps with steep slopes		

DEFINITION OF INDICATORS

For a greater understanding of the journey from the user's perspective, the areas a journey comprises were separated. These areas will be called "Travel Moments" and will be defined as:

- Moment 1: ENTRANCE-E: This includes all the spaces from the exterior entrance and main accesses to the ticket office area, which are the access by fixed stairs, escalators, or elevators, including their connections with the different areas they comprise, either the vending and rail-card charging machines area, ticket office windows, connection with the turnstile and elevators that go to the platform, among others.
- Moment 2: TOWARDS PLATFORM-P: This includes the route from the turnstile to the platform area. It includes internal stairs, escalators, elevators, and the platform itself.
- Moment 3: COMBINATION-C: This involves all the parameters detected from when a user leaves the train to the combination to another line or intermodal station. This parameter only applies to stations with a combination with other lines or a connection with some intermodal station.

To analyze the level of accessibility of each of the travel moments, different indicators related mainly to spatial physical barriers were evaluated, which together gave a score. The scores of each indicator were averaged according to the station's configuration, and based on the final score obtained, the level of accessibility was provided. The scale to evaluate the criteria is VG (very good),

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2 points; G (good), 1 point; B (bad), 0 points.

Table 2 below details the number of indicators found and the ideal maximum scores for each travel moment. Then, Table 3 presents each of the indicators associated with moments E, P, or C, as appropriate, with their respective evaluation scale and associated scores.

Table 2. Number of indicators and ideal scores associated with the moments. Source: Preparation by the authors.

Moments	Number of indicators	Ideal Score
Entrance (E)	24	48
Platform (P)	9	18
Combination (C)	15	30

Table 3. Evaluation indicators. Source: Preparation by the authors.

Moment	Indicator	Evaluation scale		
		Very Good (2p)	Good (1p)	Bad (0p)
E	Main access screen	There is information on the status of the metro	This is information, but it is not updated	Does not exist
E/P/C	Staircase handrails	It has two handrails. One at 90 cm from the FFL and the second at 60 cm from the FFL. And a diameter between 3.5 to 5.0 cm (Figure 2a)	It has one handrail at a height of 90 cm from the FFL and a diameter of 3.5 to 5.0 cm.	There are handrails, but they have a height and diameter different from those established. (Figure 2b)
E/P/C	Escalators	They are two-way	They are one-way	Does not exist
E/P	Elevator and stairlift	There are, and they both work	There is one or one that does not work	Non-existent, or neither of them work
E/P	Tactile warning	Color contrast at the beginning and end of all stairs and access to cars (platform limit)	Color contrast in some accesses to cars and stairs	Does not exist
E/P	Flight of stairs	Sections of 15 steps separated by a break of at least 120 cm	Sections between 16 to 18 steps separated by a break	Flights of more than 18 steps without a break
E/P	Stair tread and riser	Tread 28 cm and riser 18 cm	Tread less than 28 cm or riser more than 18 cm	Tread less than 28 cm and riser more than 18 cm
E	Tactile guide connection at entrance	There is a connection between stairs, ticket office, and turnstile. (Figure 3a)	There is a partial connection between stairs, ticket office, and turnstile.	Non-existent (Figure 3b)
E	Tactile guide connection to the elevator that leads to the outside	Elevators, ticket office, turnstile, and preferential door access are fully connected.	A partial connection exists between elevators, ticket office, turnstile, and preferential door access.	Does not exist
E	Ticket office window	Preferential with suitable height for PWD	Preferential without suitable height for PWD	Does not exist
E	Recharging/consultation/ purchase machines	There are. Suitable height between 90-120 cm from the FFL	There are. Without a suitable height between 90-120 cm from the FFL	Non-existent
E	Recharging/consultation/ purchase machines at the ticket office	They have a voice and Braille navigation system.	They have a voice or Braille navigation system.	There is no navigation system.
E	Entrance door for wheelchairs and pushchairs to the platform	Configurable two-way door.	Manual door	Non-existent or help must be asked to use it

Moment	Indicator	Evaluation scale		
		Very Good (2p)	Good (1p)	Bad (0p)
E	Elevator	The size allows a wheelchair to enter, turn around, and leave (150 cm in diameter). Alternatively, it allows entry and exit in the direction of travel.	110 by 140 cm in size, only allows a wheelchair to enter (forwards)	Is not big enough for a wheelchair or does not work
E	Elevator door	Minimum width: 90 cm. Automatic and sliding opening.	Minimum width: 90 cm. Manual and folding opening.	It does not have an elevator, or it does not work.
E/C	Elevator buttons	Located at a height between 90-120 cm from the FFL (horizontal preference)	Some are located at a height of more than 120 cm from the FFL	Located more than 120 cm from the FFL, they do not work, or there is not one
E	Elevator Command buttons with embossed Braille system	All have them. Suitable height.	Some have them. Or unsuitable height	Without Braille system
E/C	Audio and screen in the elevator to announce the level	Both working	There is one or just one works	Non-existent or damaged
E	Elevator ramp access	There is side protection on the entire slope when it is > 150 cm in length.	There is side protection on only part of the slope when it is < 150 cm in length.	There is one without side protection.
E	Elevator exit space	Allows maneuvering (diameter 150 cm)	Allows maneuvering with difficulty (diameter < 150 cm)	Non-existent or with obstacles
E	Security camera and call button in the elevator	Both working	There is one or just one works	Non-existent or damaged
E	Sound and light signal in the elevator to notify doors are closing	Both working	There is one or just one works	Non-existent or damaged
E	Tactile guide elevator entrance and exit	There is tactile warning and color contrast.	There is only yellow color contrast	Does not exist
E/P	Location information (exits, combination, emergency exits, information murals, location of elevators)	Has good lighting, suitable height, and without obstacles	Has some obstacles that prevent seeing it	Does not have good lighting or suitable height and has obstacles
P/C	Route	There are no gaps in the route	There are gaps but with protection	There is no protection for the gaps
P	Platform tactile guide	There is one, and it is connected with a vertical exit element (Figure 4a)	There is one but without a connection	Does not exist (Figure 4b)
P	Preferential waiting area	Close to elevators and stairs	Away from elevators or stairs	Does not exist
P	Tactile warning /color contrast at the end of the platform	Both	Only a yellow stripe, no tactile tread	Non-existent
P	Platform seats	All at 46 cm from the FFL	Some less than 46 cm from the FFL	Non-existent, or some are more than 48 cm from the FFL
P	Digital information element on the status of stations, metro, and train lines.	Electronic screens and televisions.	Only televisions	Non-existent, they cannot be read, or they do not work.

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Moment	Indicator	Evaluation scale		
		Very Good (2p)	Good (1p)	Bad (0p)
P/C	Informative plans (platform) Line change information (combination)	They have good lighting, no obstacles, and are suitable to be seen by PiW.	They do not have good lighting, have obstacles, or are at a height that does not allow them to be seen by PiW.	Does not exist
P	Vertical and horizontal differences between platform and train	Does not exist	Minimum difference	There are many differences. The PWD needs help to get in/out.
C	Tactile guide connection between elevators connecting two lines	It is continuous	it is interrupted	Does not exist
C	Tactile guide connection between stairs connecting two lines	It is continuous	Only at the beginning or end of the stairs	Does not exist

Here are some excellent examples of the indicators (a) and others that need attention (b):

Figure 2a. Example of a staircase with double handrails on its edges. Source: Preparation by the authors

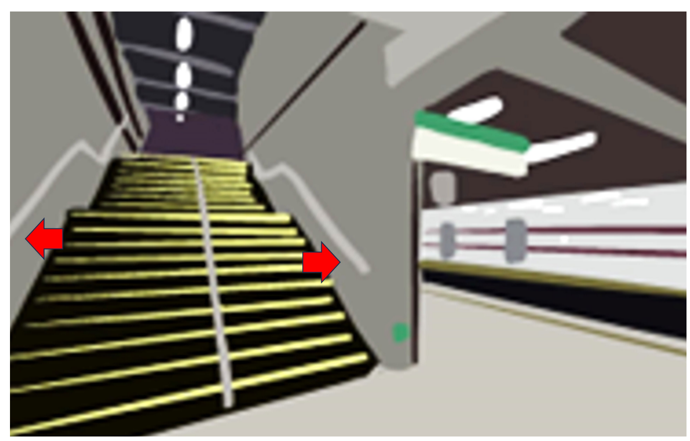

Figure 2b. Example of a staircase with a single handrail (at the edges and center). Source: Preparation by the authors

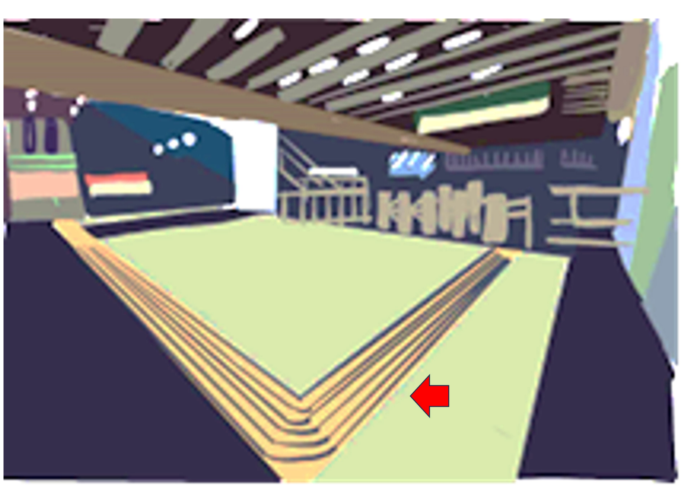

Figure 3a. Example of a complete connection of the tactile tread between the ticket office and the access to the turnstiles. Source: Preparation by the authors

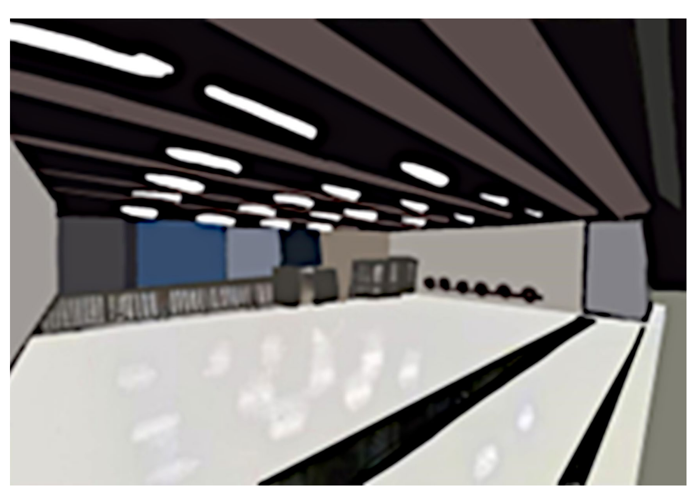

Figure 3b. The entrance to a station has no tread, only colors on the pavement. Source: Preparation by the authors

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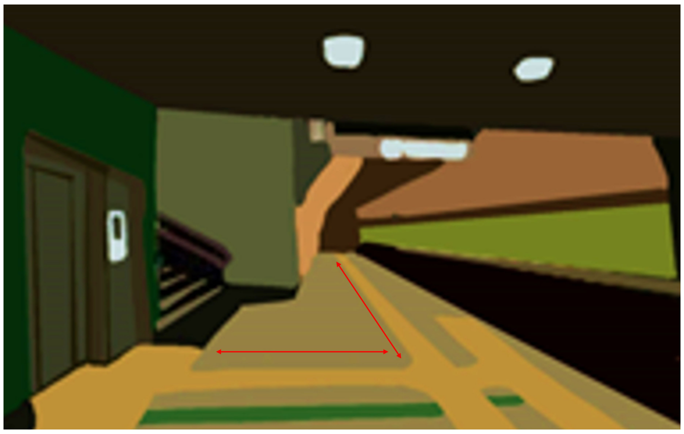

Figure 4a. Tactile tread on the platform that connects throughout its route with a vertical exit element (elevator).
Source: Preparation by the authors

Figure 4b. The platform has no tactile tread (only a yellow stripe that warns of its edge).
Source: Preparation by the authors

It is important to note that, due to the characteristics and constructive systems in each station, not all the indicators are necessarily applied, so not all of them could obtain the maximum scores indicated by travel moment (Table 3). For this reason, the percentage compliance at each travel moment was calculated. The sum of all the moments gives the total score per station. The division of the total score obtained versus the total possible score gives the percentage compliance with the accessibility levels defined in Table 4.

Table 4. Levels of accessibility. Source: Preparation by the authors.

% compliance	Levels of accessibility
80% - 100%	Very Well Adapted
60% - 79%	Well Adapted
40% - 59%	Partially Adapted
20% - 39%	Poorly Adapted
< 20%	Very Poorly Adapted

The application of the methodology is shown through the results of 5 stations selected for their special systems and configurations:

Underground Station (Bellas Artes)
Elevated station with two levels (San Joaquin)
Elevated station with 5 levels (Mount Tabor)
Combination station with another line (Ñuble)
Combination station with an intermodal station (Bellavista de La Florida).

EVALUATION OF THE STATIONS

Of the five stations evaluated, the Bellavista de la Florida station (underground, intermodal connection and access to shopping center, identified with letter E in Figure 1) was the one that obtained the lowest percentage as a station (52%), at the entrance (56%) and combination (39%). The low evaluation is due, among other aspects, to the fact that the main entrance does not have elevators, escalators, or access ramps. Thus, the only way that PWD can access or leave the station is by requiring the help of guards or companions. Also, the combination with the namesake intermodal does not have a good connection and accessibility. One of the problems detected regarding communication for intermodal access that mainly affects people with cognitive disabilities is the use of information panels with contradictory information (Figure 5). On the other hand, a problem identified affecting people with visual impairments is the lack of a tactile tread at the beginning and end of stairs (Figure 6).

Figure 5. Contradictory information on the intermodal connection route panels (where two different directions are observed).
Source: Preparation by the authors

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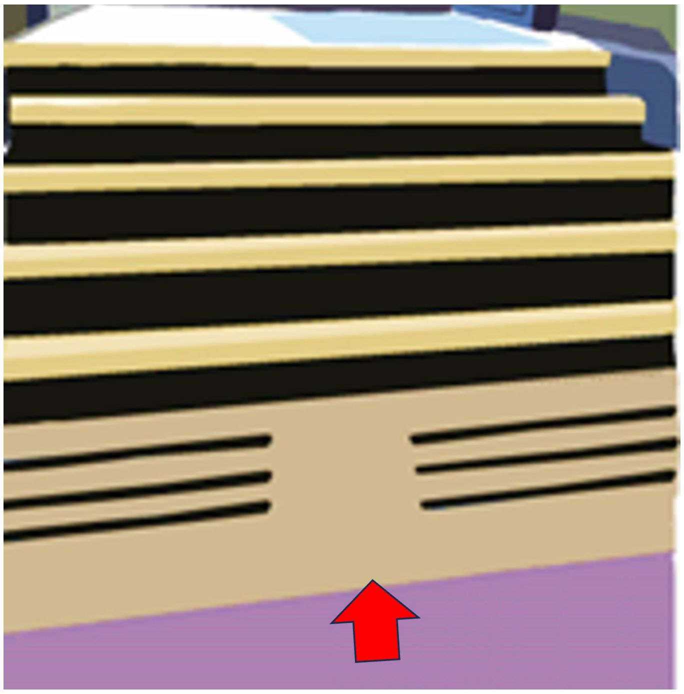

Figure 6. Lack of a tactile tread on the access to stairs that are only identified with a yellow stripe.
Source: Preparation by the authors

On the contrary, the Ñuble station (station with street level entrance, elevated platform, and combination with another line, marked with the letter C in Figure 1) is the one that obtained the highest percentage (69%). This is mainly due to its connection with Line 6 (inaugurated in 2017), whose design implied improved accessibility issues. Its ENTRY and COMBINATION criteria obtained high scores (71% and 78%, respectively). However, the platform area had a low rating due to the lack of tactile tread and its connections with the stairs, which affected its overall evaluation. This station is the only one on Line 5 with automatic access at its main entrance and machines adapted for all users.

Meanwhile, the San Joaquin station (station area with access to universities and medical centers, marked with the letter D in Figure 1) reached 57%. Like most stations, its lowest score is presented in PLATFORM (53%), mainly due to its lack of tactile tread and connection with the elevator and stairs. The station has only one elevator that is not always operational, which forces PWD to request help from guards or companions or even to go to the next station to access or exit the metro system.

The next station evaluated, which is Bellas Artes (underground station, access to the historic center of the city, marked with the letter B in Figure 1), does not have a tactile tread on the main access that connects to the ticket office or along the platform, which makes it difficult for visually impaired people to move around. In addition, the seats are well above the required 45 cm high. Nor does it have escalators or stairlifts if the elevators do not work. That is why its overall accessibility level (58%) is affected by the PLATFORM indicators (50%).

Finally, the Monte Tabor station (elevated station, shopping center access, identified with the letter A in Figure 1) has its lowest score in PLATFORM (57%), again due to the lack of a tactile tread, including its connections with elevators and stairs. Even so, it received a good score in ENTRANCE (69%) for having two-way escalators.

Table 5 summarizes the results of the application of the evaluation in each of the moments a journey comprises in the Santiago Metro, analyzing Entrance (E), Platform (A), and Combination (C).

Table 5. Results of the evaluated stations. Source: Preparation by the authors.

Station	E	P	C	Average	Level station
Bellavista de La Florida (letter E - Figure 1)	27/48 56%	18/30 60%	7/18 39%	52%	Partially Adapted
San Joaquín (letter D - Figure 1)	28/46 61%	16/30 53%		57%	Partially Adapted
Ñuble (letter C - Figure 1)	10/14 71%	17/30 57%	14/18 78%	69%	Well Adapted
Bellas Artes (letter B - Figure 1)	32/48 67%	15/30 50%		58%	Partially Adapted
Monte Tabor (letter A - Figure 1)	29/42 69%	17/30 57%		63%	Well Adapted

CONCLUSION

Based on the different problems PWD have when using public transport, it was possible to raise a series of indicators, mainly related to spatial physical barriers, which allowed the creation of a tool for assessing the level of accessibility in the Santiago de Chile Metro network. It was concluded from its application in some representative stations that most old stations obtained the lowest scores in the "PLATFORM" criterion but good results in the "ENTRANCE" criterion, mainly due to recent elevator installations in those stations.

Although Metro de Santiago S.A. has indeed made improvements on the issue of accessibility, these have focused on physical disability and, therefore, are still insufficient in incorporating the needs of other disabilities. This situation allows making the recommendation that the next adaptation and remodeling works should focus on those criteria with the lowest scores obtained by the stations to improve their level of accessibility. In addition, to expand the vision of accessibility in public transport, evaluating other spaces, such as intermodal connections or the space surrounding a Metro station, would be interesting.

On the other hand, as the work focused on analyzing spatial physical barriers, it was easier to assess the needs of people with physical or visual disabilities onsite. Although an attempt to incorporate indicators for people with hearing or cognitive disabilities, in the next version of the methodology, more sensory aspects could be analyzed in the analysis.

Finally, it is important to mention that, given the relevance of accessibility issues, regulatory changes that are being updated should be continuously considered (such as SD30, which was modified after conducting this study). The contribution of this proposal is that it is evolutionary and includes, eliminates, or updates the indicators presented here.

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MANUFACTURE OF LIGHTENED MORTARS WITH PERLITE AND LIME APPLIED IN PANELS WITH A RICE STRAW RESIDUE MIX

FABRICACIÓN DE MORTEROS ALIGERADOS CON PERLITA Y CAL APLICADOS EN PANELES CON MATRIZ DE RESIDUOS DE PAJA DE ARROZ

FABRICAÇÃO DE ARGAMASSAS LEVES COM PERLITA E CAL APLICADAS EM PAINÉIS COM MATRIZ DE RESÍDUOS DE PALHA DE ARROZ

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RESUMEN

La presente investigación tiene como objetivo diseñar y caracterizar morteros de revoco a base de perlita y cal producida en Ecuador, con una resistencia mínima a compresión de 6.89 MPa, conforme lo establece el IRC 2018. Esto, con el fin de ser aplicado sobre paneles elaborados con paja de arroz. Para ello, se diseñan 2 mezclas patrón. En la primera se usa arena como árido fino, mientras que para la segunda se usa perlita. De cada una se obtienen 8 mezclas adicionales, en las que se sustituye el cemento por cal (en volumen) en diferentes porcentajes. Se realizan 270 probetas con la finalidad de evaluar la resistencia a compresión y la densidad de los morteros a 1, 3, 7, 28 y 50 días. El mortero elaborado con perlita y compuesto por 50% cal, 50% cemento y aditivo, alcanzó una resistencia de 7.22 MPa, con una densidad de 1.45 g/cm³. Al aplicar esta mezcla sobre los paneles elaborados con paja de arroz, dio como resultado el aumento de su resistencia a compresión hasta un 68%.

Palabras clave
revoco; mortero; paja

ABSTRACT

This research aims to design and characterize plaster mortars based on perlite and lime produced in Ecuador, with a minimum compressive strength of 6.89 MPa, as established by IRC 2018, to be applied on rice straw panels. For this purpose, two standard mixes are designed. In the first, sand is used as fine aggregate, while in the second, perlite is used. Eight additional mixes are obtained from each one, where cement is replaced by lime (in volume) in different percentages. A total of 270 test specimens were made to evaluate the compressive strength and density of the mortars at 1, 3, 7, 28, and 50 days. The mortar made with perlite, comprising 50% lime, 50% cement, and an additive, reached a resistance of 7.22 MPa, with a density of 1.45 g/cm³. When this mixture was applied to the rice straw panels, it resulted in an increase of up to 68% in their compressive strength.

Keywords
plaster, mortar, straw

RESUMO

O objetivo desta pesquisa é projetar e caracterizar argamassas de reboco à base de perlita e cal produzidas no Equador, com uma resistência à compressão mínima de 6,89 MPa, conforme estabelecido pelo IRC 2018. Isso, para ser aplicado em painéis feitos com palha de arroz. Para isso, foram projetadas duas misturas padrão. Na primeira, a areia é usada como agregado fino, enquanto na segunda, é usada perlita. A partir de cada uma delas, são obtidas 8 misturas adicionais, nas quais o cimento é substituído por cal (em volume) em diferentes porcentagens. Foram feitos 270 corpos de prova para avaliar a resistência à compressão e a densidade das argamassas em 1, 3, 7, 28 e 50 dias. A argamassa feita com perlita e composta por 50% de cal, 50% de cimento e aditivo, atingiu uma resistência de 7,22 MPa, com densidade de 1,45 g/cm³. Quando essa mistura foi aplicada aos painéis feitos com palha de arroz, ela resultou em um aumento de até 68% na resistência à compressão.

Palavras-chave:
reboco, argamassa, palha.

INTRODUCTION

A study by Stephan and Athanssiadis (2018) concluded that, in the last 100 years, the world's population has increased fourfold, while the consumption of materials extracted from the Earth's crust has done so tenfold, the main driver being the construction industry. According to the same study, construction minerals saw a 42-fold increase to 2010 (Stephan & Athanssiadis, 2018). The relationship between these data is not random, as population growth results in a need for more housing and infrastructure, which, in turn, allows commerce and the economy to develop (Mendoza & Vanga, 2021).

In this sense, industrial development and population growth have also resulted in more construction waste, such as fly ash, silica fume, glass, concrete waste, and steel offcuts, among others (Sudharsan & Sivalingam, 2019). For this reason, it has become necessary to study materials where circular economy criteria prevail and the creation of new products is encouraged (Zhang et al., 2018) while being in tune with the need to minimize waste and reduce energy consumption (Fernández et al., 2020).

In this context, several research projects have pointed out that panels with straw, wood, and mortar are an alternative for sustainable construction. In these, straw, often burned and discarded by farmers, causing environmental pollution through CO_2 emissions (Teslík, 2021), is the primary material. When used in construction, this agro-industrial waste provides solutions that offer quality economic development, social welfare, and environmental respect (Cascone et al., 2019). According to statistical data, 1,132,267 tons of rice were produced in Ecuador in 2010, covering an area of 382,230 hectares (Ministry of Agriculture and Livestock of Ecuador, 2022), which generates a large amount of waste (straw) that could be used.

On the other hand, straw panels are manufactured by taking the straw bales directly from the agricultural producer or using a manual baler. Then, they are accommodated discontinuously inside a wooden frame, whose dimensions allow making a panel that fits the architectural design of a house. The plaster mortar consists of a mixture of aggregates (sand or perlite) and conglomerates (lime and cement) in proportions to protect the straw from external agents and improve the panel's structural properties.

The energy required to make the panels and build with them is negligible due to their easy assembly and disassembly. In addition, they provide a very high thermal resistance, adequate ventilation, greater comfort, and fire safety compared to traditional materials (Muntani et al., 2020). For this reason, buildings that use rice straw panels and coating mortars consume very little energy. They are also sustainable since, at the end of their useful life, the wood can be recovered or incinerated, the straw composted, and the lime used in the soil to improve agricultural fields (Martínez, 2019).

The coating mortar or plaster on the panels has several important roles. One of these is to control the humidity inside it and thus prevent the straw from rotting (Walker et al., 2020). It also protects them from external agents such as rain, sun, and even insects or organisms that may alter their useful life (Martínez, 2019). Therefore, it is essential to study innovative materials as replacement alternatives to Portland cement for manufacturing these mortars in different proportions or their entirety (Aprianti, 2017).

One alternative is hydrated lime or calcium hydroxide ($Ca(OH)_2$). However, it has been studied very little for these purposes due to the emergence of cement in construction (Apostolopoulou et al., 2021). This material is considered sustainable, as it can generate 50% less pollution compared to the industrialization process of cement (Hermida, 2021).

Due to the reaction between this material and the gases in the atmosphere during the setting process, as lime traps CO_2, the mortar hardening times tend to be slower, unlike hydraulic binders (Pahlavan et al., 2018). However, over time, this chemical process allows the cracks in the hardened mortar to self-seal, providing greater durability and water vapor permeability thanks to the lime increasing the contact between the fine aggregate particles (Zhang et al., 2018).

The main objective of this research is the design and characterization of a lime and perlite-based mortar. This is to use it as plaster in straw-based panels obtained as waste from the rice harvest with ideal structural parameters for housing construction. Said plaster must also provide the panel with suitable strength, less weight, and sustainability conditions by permitting the highest amount of lime in its mixture to replace cement. It must be checked, therefore, that the use of lime instead of cement in the mortar maintains the required strength limits of 6.89 MPa, following

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the American standard for straw construction IRC 2018 (Table 1) and the Ecuadorian NTE INEN (Ecuadorian Institute of Standardization) and international ASTM standards (*American Society of Testing and Materials*) for mortar design.

Table 1: Minimum compressive strength of plasters for straw-made walls. Source: (IRC, 2018)

Type of plaster	Minimum compressive strength	
	(PSI)	(MPa)
Clay	100	0.69
Soil - Cement	1000	6.89
Lime	600	4.14
Cement - Lime	1000	6.89
Cement	1400	9.65

Straw, like wood, degrades over time in the presence of moisture (Yin et al., 2018). Therefore, researching materials such as lime to design plasters that control humidity and guarantee the harmony between wetting and drying ensures the durability and good behavior of buildings made with straw (ESBA, 2021). Those mortars that have a higher amount of lime in their composition have acceptable permeance and permeability (Pavia & Brennan, 2018) to prevent straw rot.

Consequently, mortars must not only meet the indicated strength but have a density that is as low as possible due to the large volume it occupies in the panel. For this reason, some mortars are designed with sand and others with perlite, a fine, low-density aggregate with a porous texture that can retain water on its surface (Artigas et al., 2022).

Currently, there are few studies on the use of lime and perlite in mortars for this purpose. However, one by Viera and Acero (2022) can be highlighted, which evaluates the compressive strength of mortars from lime produced and marketed in Ecuador for use as glue in masonry. The highest compressive strength, equal to 3.5 MPa after 28 days, is obtained with lime from the La Paz quarry. It also characterizes four additional limes (San Juan, San José, Incoreg, Indami) with lower strength.

In this sense, to promote materials such as perlite, lime, and straw, it is necessary to perform studies that determine their physical and mechanical characteristics, individually and jointly, such as with the panel. These also provide data that allow construction professionals to make the respective modeling and structural analysis of buildings with prefabricated straw. This research provides relevant data about the dosage and strength of low-density mortars with lime and perlite content, which can be an alternative in conventional and sustainable constructions when applied on the panel.

METHODOLOGY

The procedures established in the Ecuadorian NTE INEN and the ASTM international standards were followed in this research. These were used in the characterization of both the materials in the mortar, as well as the evaluation of its properties as a whole and to determine the compressive strength in the straw panels.

Figure 1 summarizes the methodology for the research, explained in detail in the following sections. The study starts by selecting the materials and their characterization to then design two standard mixtures, SM1 (cement + sand + water) and SM2 (cement + perlite + water), using the optimal density method. From each of these mixtures, eight additional variants are obtained where cement is replaced by lime in percentages of 30%, 50%, 70%, and 90%. Additives are also added to some of these.

A total of two hundred and seventy 50 mm cubic specimens were made with each study mixture to determine the density and compressive strength of the mortars at 1, 3, 7, 28, and 50 days. The mixture chosen will be the one that allows obtaining a low-density mortar with a higher lime content and an optimal strength that is equal to or greater than 6.89 MPa at 28 days, as established by the construction code for straw, IRC 2018 so that it can be used on walls.

Finally, the chosen mixture will be applied on the external faces of 3 prefabricated panels with wooden frames and previously baled rice straw. It will then be tested under compression to obtain its ultimate load, strength, and weight. The compression test is also performed on 3 additional panels where the coating has not been applied to determine the functionality and contribution of the mortar inside the panel against these load stresses.

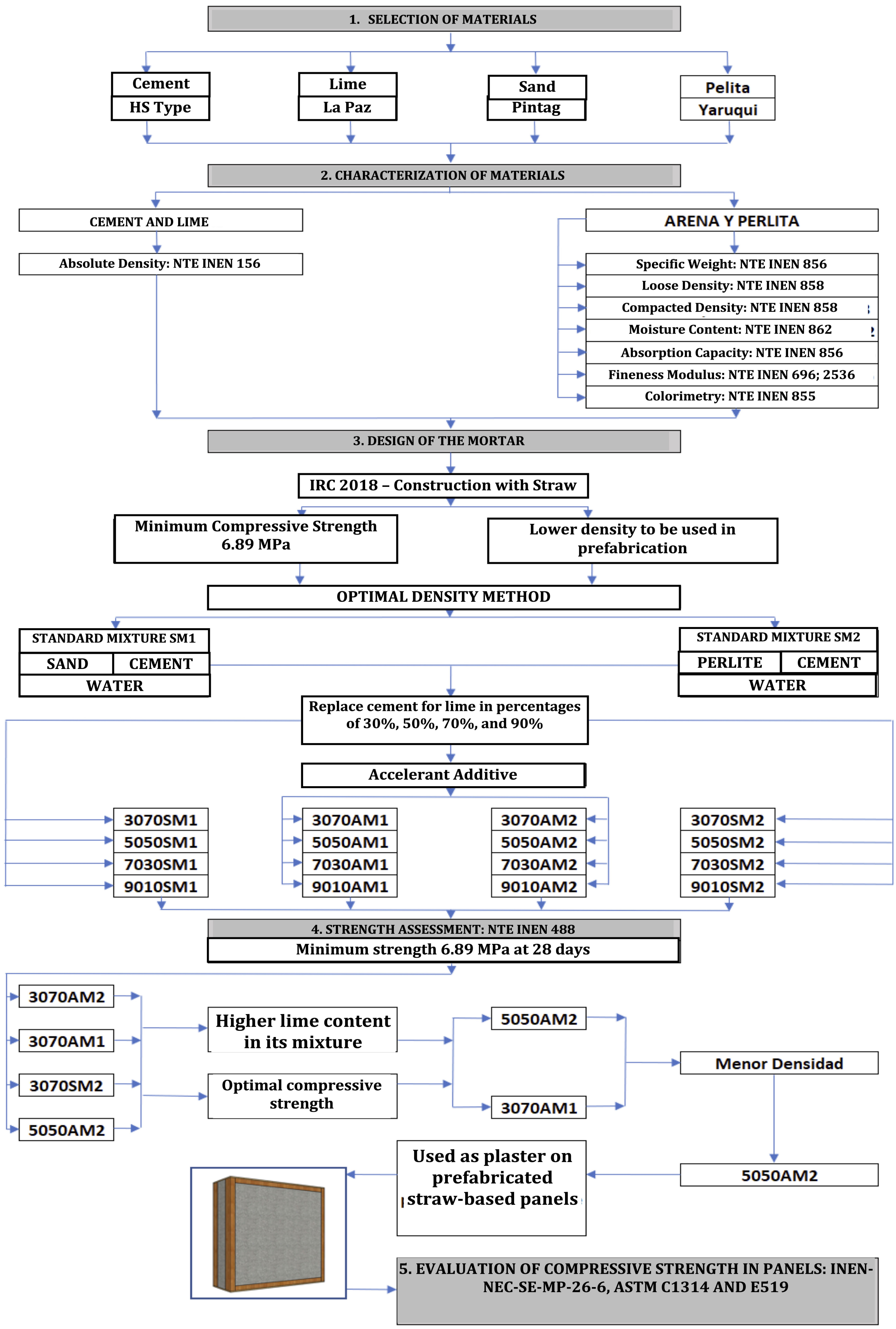

Figure 1: Research methodology. Source: Preparation by the authors.

MATERIALS

Sulfate-resistant hydraulic cement, whose absolute density is 2.80 g/cm^3, was used to make the mixtures. The physical properties of the HS cement are indicated in Table 2 below, following what is indicated by NTE INEN 2380 and ASTM C1157.

Table 2: Physical properties of the cement. Source: (NTE INEN 2380, 2011)

Physical Properties	NTE INEN	ASTM	HS Type Cement
Change of length by autoclave (%)	200	C-490	0.80
Initial setting time (min)	158	C-191	≥45≤120
Compressive strength (MPa)	488	C-109	3rd day = 11 7th day = 18 28th day = 25
Mortar bar expansion 14 days (%)	2529	C-1038	0.020
Sulfate expansion / Sulfate resistance (%)	2503	C-1012	6 months = 0.05 1 year = 0.10

Nationally produced hydrated lime was used, extracted from the La Paz lime mill (Carchi – Ecuador), as a replacement for cement in different percentages (30%, 50%, 70%, and 90% by volume). According to its use and the NTE INEN 247 standard, this is classified as type N (Normal lime without incorporated air used in cement mortars and plasters). The physical-chemical properties of this lime are indicated below in Table 3.

Table 3: Physical-chemical properties of the lime. Source: Preparation by the authors.

Physical-Chemical Properties	NTE INEN	ASTM	Lime Type N
Absolute density (g/cm³)	156	C-144	2.20
Loose bulk density (g/cm3)	858	C-29	0.82
Compacted bulk density (g/cm3)	858	C-29	0.90
Residue sieve No. 30 (%)	244	C-110	23.20
Calcium oxides (%)	250	C-25-19	36.00
Magnesium oxides (%)	250	C-25-19	1.90

In the first design of mixtures to make the mortar, sand from the quarry located in the parish of Pintag (Quito – Ecuador) was used as a fine aggregate, while, for the second design, perlite from the Yaruquí parish (Quito – Ecuador) was used. Both materials comply with the granulometry to be used in mortars according to the NTE INEN 2536 standard. The granulometric curves of the aggregates are indicated below in Figure 2 and Figure 3.

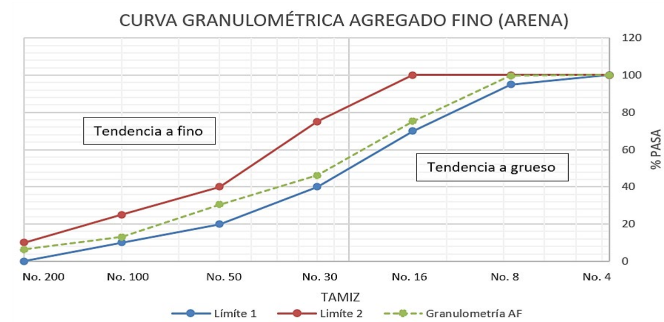

Figure 2: Granulometric curve of the sand. Source: Preparation by the authors.

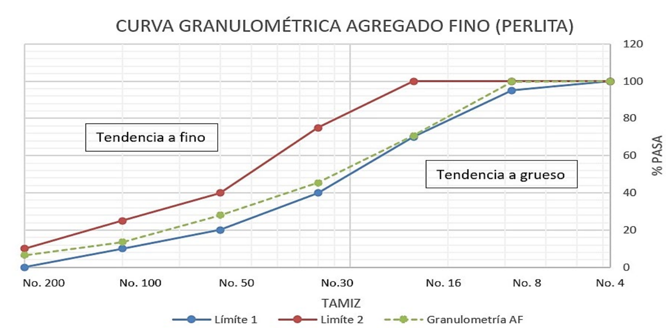

Figure 3: Granulometric curve of the perlite. Source: Preparation by the authors.

The appearance of perlite is similar to polystyrene beads (as shown in Figure 4). It is used in construction when it is necessary to improve the thermal and acoustic properties and obtain greater lightness (El Mir et al., 2020). Incorporating perlite in the mixtures allows comparing the mortar's densities to find one that is as light as possible in balance with its compressive strength.

Tests are run for sand, perlite, cement, and lime to identify their specific weight, loose and compacted density, moisture content, absorption capacity, granulometry, fineness modulus, and colorimetry. This is shown in Figure 5.

Figure 4: Perlite. Source: Preparation by the authors.

Figure 5: Laboratory tests: a) cement and lime, b) perlite, c) sand. Source: Preparation by the authors.

The results of the tests run on the sand and perlite are shown below in Table 4.

Table 4: Physical properties of the sand and perlite. Source: Preparation by the authors.

Physical Properties Test	NTE INEN	ASTM	Sand	Perlite
Specific Weight (g/cm3)	856	C-127	2.41	1.44
Loose Density (g/cm3)	858	C-29	1.41	0.60
Compacted Density (g/cm3)	858	C-29	1.60	0.68
Moisture content (%)	862	C-127	1.04	3.39
Absorption capacity (%)	856	C-127	2.26	9.55
Fineness Modulus	2536	C-136	2.44	2.43
Colorimetry	855	C-40	WOM	WOM

WOM: Without organic matter

Using lime in mortar mixtures delays setting times and decreases its strength at early ages. For this reason, using an accelerator additive (Plastocrete 161 HE) with a density of 1.10 kg/dm^3 has been necessary. Its dosage can vary between 0.2% and 2.5% of the cement's weight and is manually added to the kneading water.

On the other hand, the rice straw used to make the panels was previously baled, and its physical properties are indicated in Table 5.

Table 5: Physical properties of straw bales. Source: Preparation by the authors.

Physical Properties	Bale
Dimensions (cm)	35x45x120
Absolute density (kg/m3)	84.00
Moisture content (%)	13.00
Weight (kg)	12.90

DESIGN OF THE MIXTURES

Two standard mix designs, SM1 and SM2 here, were made using the optimal density method. Both had a design strength of 12.40 MPa, corresponding to type S cement and lime mortars (which have better adhesion and use in coatings) according to the NTE INEN 2518 standard. Variants were generated from these base mixtures where the cement was replaced by lime in different proportions to find the optimal percentage that guarantees a minimum mechanical strength of 6.89 MPa, according to the parameters of the IRC 2018 code.

In the SM1 design, water, cement, and sand were used. In contrast, in the SM2 design, perlite was used as a fine aggregate since it has a low density, is easily accessible in the local environment, and has a cost similar to that of sand. Eight variants were obtained from each of these mixtures, where an additive was added to 4 mixtures (strength accelerator additive at 2.5% of the weight of the cement), and no additive was added to the remaining 4. In addition, cement was replaced by lime in proportions of 30%, 50%, 70%, and 90% in each group of mixtures. The methodology used to obtain the mixtures is summarized in Figure 6.

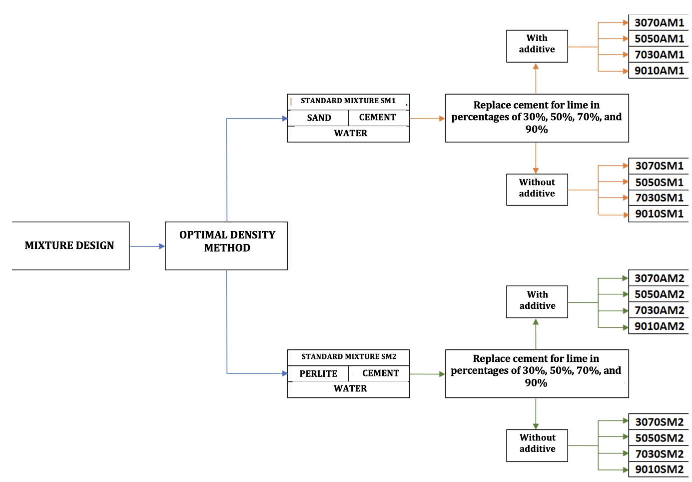

Figure 6: Methodology to obtain the mixtures. Source: Preparation by the authors. Source: Preparation by the authors.

The coding indicated in Figure 7 was used for the mixtures obtained, for example, the mixture 9010AM1.

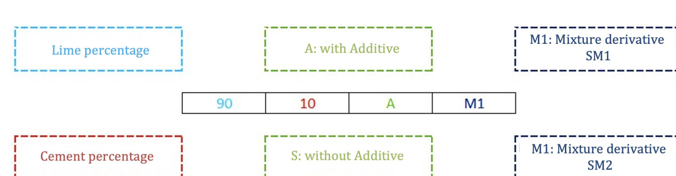

Figure 7: Coding for the study mixtures. Source: Preparation by the authors.

Table 6: Dosage in kilograms for one cubic meter of mortar. Source: Preparation by the authors.

Id.	Lime (kg)	Cement (kg)	Fine Aggregate (kg)	Water (kg)	Additive (kg)
MP1	0.00	339.63	1446.50	392.29	0.00
9010AM1	240.17	33.96	1446.50	390.29	8.49
9010SM1	240.17	33.96	1446.50	390.29	0.00
7030AM1	186.80	101.89	1446.50	370.75	8.49
7030SM1	186.80	101.89	1446.50	370.75	0.00
5050AM1	133.43	169.82	1446.50	370.29	8.49
5050SM1	133.43	169.82	1446.50	370.29	0.00
3070AM1	80.06	237.74	1446.50	342.86	8.49
3070SM1	80.06	237.74	1446.50	342.86	0.00
MP2	0.00	523.63	552.40	404.88	0.00
9010AM2	370.28	52.36	552.40	408.31	13.09
9010SM2	370.28	52.36	552.40	408.31	0.00
7030AM2	288.00	157.09	552.40	383.05	13.09
7030SM2	288.00	157.09	552.40	383.05	0.00
5050AM2	205.71	261.82	552.40	371.62	13.09
5050SM2	205.71	261.82	552.40	371.62	0.00
3070AM2	123.43	366.54	552.40	360.20	13.09
3070SM2	123.43	366.54	552.40	360.20	0.00

The quantities in kilograms of water, cement, lime, sand, perlite, and additive for one cubic meter of mortar made with the standard mixtures SM1, SM2, and their derivatives are indicated below in Table 6.

DESCRIPTION OF THE TESTS

Mortars

All the mortars produced have a flow of 110% ± 5%, as indicated by the NTE INEN 488 standard. This property guarantees the manageability of the mixtures without generating segregation problems. Inspired by the technique used by Echeverría et al. (2022) in a similar study regarding the elaboration of sustainable panels for residential interiors through the use of banana fiber and peanut shells, 15 cubic specimens (Figure 8) of 50x50x50 mm were manufactured for each of the 18 mixtures, including the standard samples (Echeverría et al., 2022).

For this work, 270 compression tests were carried out on mortar cubes to evaluate their strength, following the guidelines established by the NTE INEN 488 standard.

Figure 8: Elaboration of cubic mortar specimens. Source: Preparation by the authors.

For each mixture, 3 test specimens were made at 1, 3, 7, 28, and 50 days. The specimens were stored in a curing chamber until they reached the specified age, following the requirements indicated in the ASTM C511 standard. Due to the presence of hydrated lime in the mortar mixtures, the test specimens were not immersed in water, but were exposed to the open air to interact with the CO_2 and then set.

The compression test of the specimens was carried out using a 200-ton universal machine (Figure 9) equipped with metal discs for an effective distribution of the load over the application area of the cube. The loading speed was 0.25 MPa/s and was controlled by an automated system.

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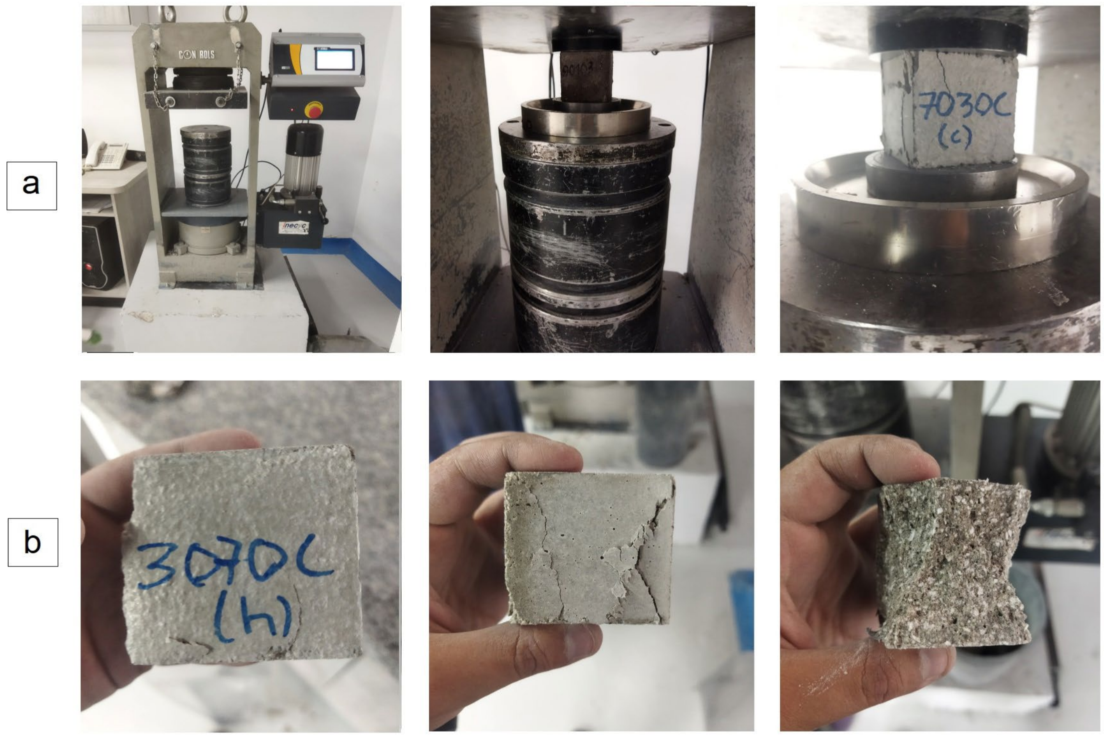

Figure 9: Compression test: a) equipment, b) cubic specimens. Source: Preparation by the authors.

Figure 10. Construction of panels Source: Preparation by the authors.

Panels

Regarding the elaboration of panels, 6 samples were built based on 1.20 m long, 1.20 m high, and 0.35 m thick straw and wooden frames. As in the previous test, the samples were divided in half, adding mortar to 3 and no mortar to the other 3 (Figure 10).

In the panels that include mortar, a 2.5 cm thick layer was applied on both sides (Figure 11), made with the 5050AM2 mixture (50% lime, 50% cement, perlite, with additive). This mixture meets the objective of this research by providing sustainability conditions and the required properties, such as strength and density.

The panels were subjected to compression tests, as shown in Figure 12, following the procedures established in the INEN-NEC-SE-MP 26-6 and ASTM C1314 standards. For the tests, a loading system consisting of a 20-ton cell and a 100-ton hydraulic cylinder controlled by a 10000Psi hydraulic pump was used. 2 LVDTs (displacement meters) were placed on the panel, connected to an 80-channel HBM UPM

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Figure 11. Application on mortar panels made with 5050AM2 mixture. Source: Preparation by the authors.

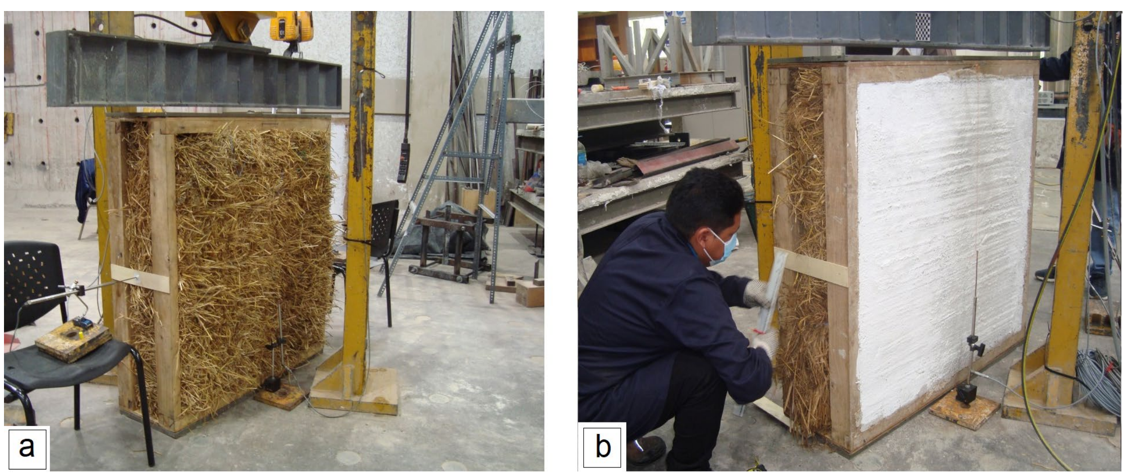

Figure 12. Compression test of panels: a) without mortar, b) with mortar. Source: Preparation by the authors.

box that records the load and displacement data. The test speed was 0.03 mm/s, as indicated in the standards.

The compression test of the panels was carried out to determine the structural capacity of the set of materials that they comprise (wooden frame, straw, and plaster), just as used in buildings. In addition, it was sought to determine whether the previously designed mortar provides strength to the panel. The axial loads applied during the test represented the dead and live loads that govern the structures. The resulting value of the panel's compressive strength will allow looking closer at the structural modeling of the constructions where this type of prefabrication is used.

RESULTS AND DISCUSSION

Figure 13 shows the compressive strength results of the mortars made from the SM1 standard mix design at different ages (1, 3, 7, 28, and 50 days). It is observed that SM1 exhibits higher compressive strength values than the other mixtures, as it contains a binder comprising 100% cement, calculated using the optimal density method. Including an additive at 2.5% of the weight of the cement in the mixtures derived from SM1 leads to an increase in its strength that varies between 20.13% and 51.52%. These findings suggest the desirability of including additives in lime mortars to reduce the setting time and achieve greater strength at an early age. In particular, the 3070AM1 mixture complies with the minimum required compressive strength of 6.89 MPa at 28 days of age, with an average strength of 7.19 MPa, exceeding the target by 0.30 MPa. This indicates its suitability to be used as plaster in buildings made with straw panels.

In addition, Figure 14 presents the compressive strength results at different ages (1, 3, 7, 28, and 50 days) of the mortars made from the SM2 standard mix design. As with SM1, the compressive strength of this mortar is superior to other mixtures due to its composition with a binder comprising 100% cement. It is important to note that this mixture contains 54% more cement than SM1, as perlite, whose density is 0.68 g/cm^3, is used as a fine aggregate. Compared to sand, whose density is 1.60 g/cm^3, a reduction of 57.5% is observed, resulting in a greater amount of paste in the mixture.

The replacement of cement by lime in SM2, in percentages of 30%, 50%, 70%, and 90%, leads to a decrease in compressive strength. As the percentage of lime in the mixture increases, and the percentage of cement decreases, the compressive strength also decreases, a behavior similar to that observed in mixtures generated from SM1. Incorporating an additive to 2.5% of the weight of the cement results in an increase in its strength that varies between 33.33% and 72.28%. In this case, the mixture that meets the minimum required compressive strength of 6.89 MPa at 28 days of age is 5050AM2, with a strength of 7.22 MPa, exceeding the target strength by 0.33 MPa. This indicates that it can also be used as plaster in buildings made with straw panels.

The results of the compressive strength at 28 days of the mortars studied in this investigation are presented in Figure 15. It is noted that there are 6 mixtures (SM1, SM2, 3070AM1, 3070AM2, 3070SM2, 5050AM2) that show a compressive strength above the required value of 6.89 MPa. The other mixtures obtained values below this threshold, so they would be discarded for use. However, of the 6 selected mixtures, two are the standard mixtures SM1 and SM2, which do not contain lime in their composition and do not meet the research objective.

Of the remaining 4 mixtures, it is observed that the mixtures 3070AM2 (30% lime, 70% cement, perlite, with additive) and 3070SM2 (30% lime, 70% cement, perlite, without additive) generate mortars with compressive strengths of 13.09 MPa and 8.90 MPa respectively, exceeding the minimum required value by 89.99% and 29.17%. On the other hand, the mixtures 3070AM1 (30% lime, 70% cement, sand, with additive) and 5050AM2 (50% lime, 50% cement, perlite, with additive) generate mortars with compressive strength of 7.19 MPa and 7.22 MPa respectively, exceeding the minimum required value by 4.35% and 4.78%. Therefore, the mixtures 3070AM2 and 3070SM2 are discarded, as their strength is well above the required one, and the mixtures 3070AM1 and 5050AM2 are accepted as preselected optimal mixtures due to their lime content and strength presented.

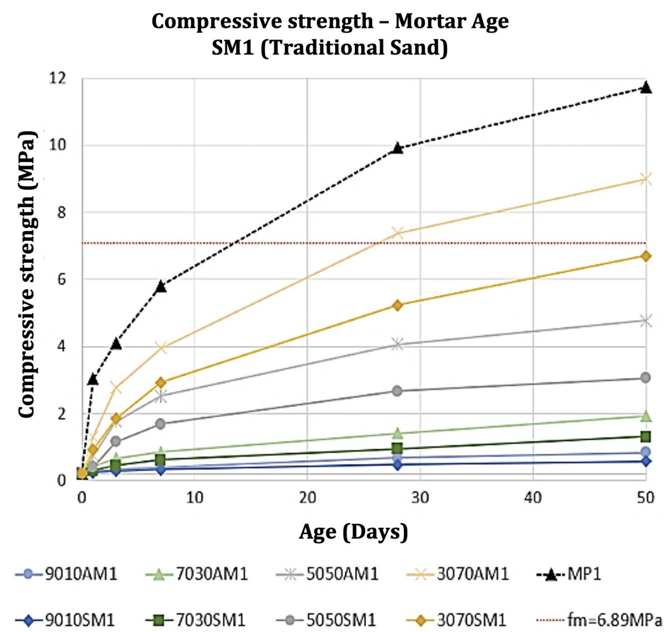

Figure 13. Compressive strength of sand-based mortars (M1). Source: Preparation by the authors.

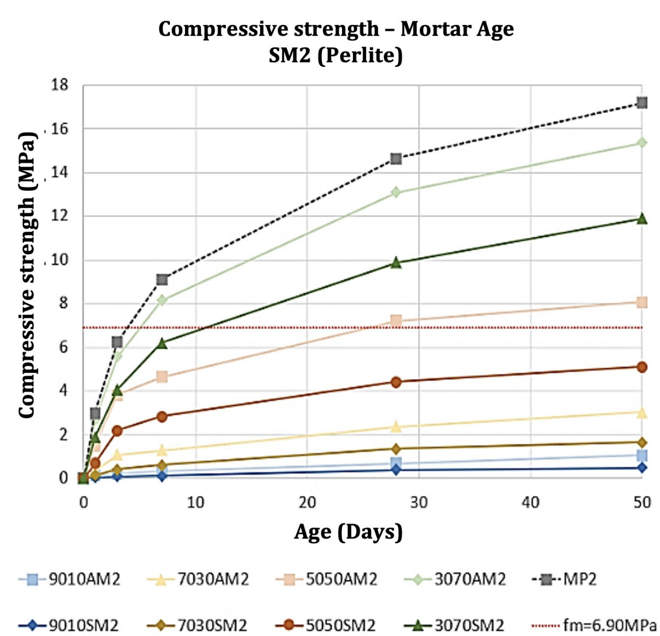

Figure 14. Compressive strength of mortars made with perlite (M2). Source: Preparation by the authors.

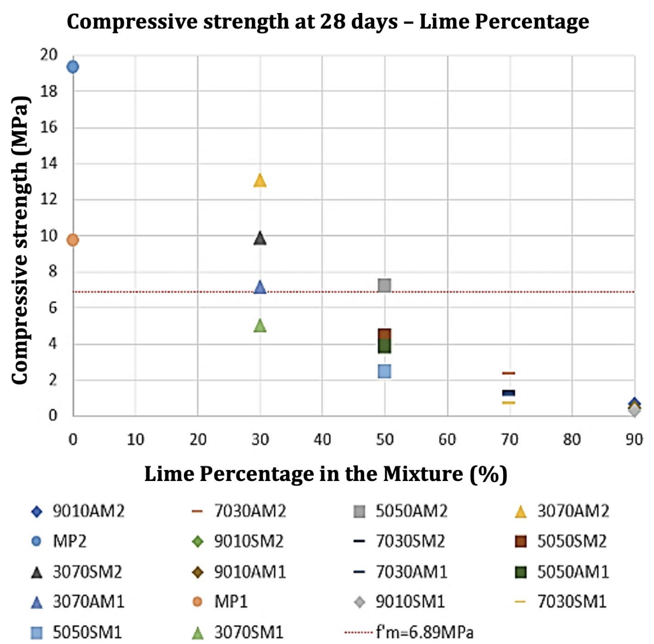

Figure 15. Compressive strength after 28 days of mortars made with sand (M1) and perlite (M2). Source: Preparation by the authors.

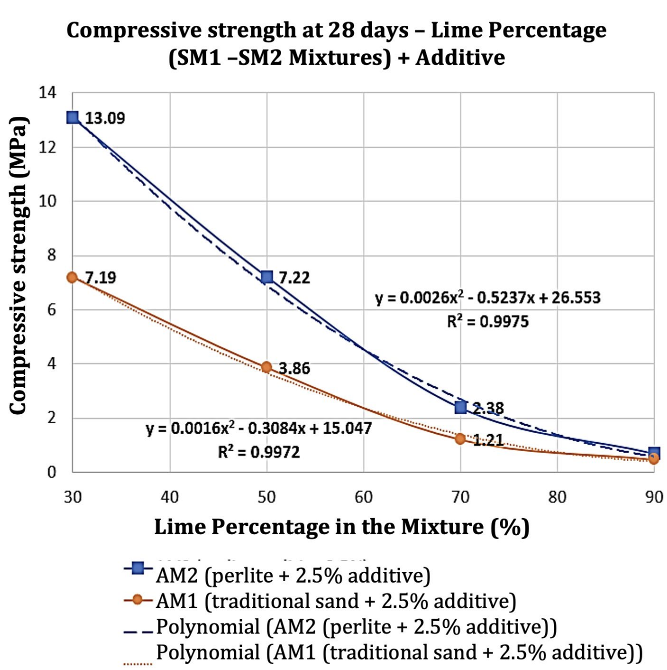

Figure 16. Polynomial adjustment compressive strength vs. percentage of lime, SM1 and SM2 mixtures with additive. Source: Preparation by the authors.

In Figure 16, the trend of the curves obtained from the results of the mixtures AM1 (cement + lime + sand + additive) and AM2 (cement + lime + perlite + additive) can be observed, which contain additives and are derived from the preselected optimal mixtures (5050AM2, 3070AM1).

Equation 1 is obtained by making the polynomial adjustment of the curves (compressive strength v/s percentage of lime). This equation allows determining the compressive strength after 28 days of mortars made from the AM1 mixture depending on the percentage of lime that is replaced by cement.

$$fm = 0{,}0016(\%limo)^2 - 0{,}3084(\%Cal) + 15{,}047$$

(Equation 1)

(Equation 2) is obtained for the AM2 mixture.

$$fm = 0{,}0026(\%limo)^2 - 0{,}5237(\%Cal) + 26{,}553$$

(Equation 2)

Where:

fm: Compressive strength in MPa.
%Lime: Percentage of lime in the mixtures replaced by cement.

The correlation coefficient (R^2), whose value for both models is 0.997, similar to 1, is determined to evaluate the validity of the equations. Therefore, both equations correctly fit the results achieved and provide very accurate estimates of compressive strength at 28 days of age to those obtained through experimentation.

Figure 17 shows the box and mustache diagrams made from the results of the densities of the mortars manufactured with the preselected optimal mixtures 5050AM2 and 3070AM1. The values of the densities were taken in cubic specimens of 50 mm at 1, 3, 7, 28, and 50 days. 6 specimens were made by age, obtaining density values for 60 mortar cubes, i.e., 30 values for each mixture.

The mortars manufactured with the 5050AM2 mixture have density values ranging between 1.34 g/cm³ as a minimum value and 1.55 g/cm³ as a maximum value, with an average density of 1.45 g/cm³. On the other hand, the mortars manufactured with the 3070AM1 mixture have densities ranging between 1.85 g/cm³ as a minimum value and 2.02 g/cm³ as a maximum value,

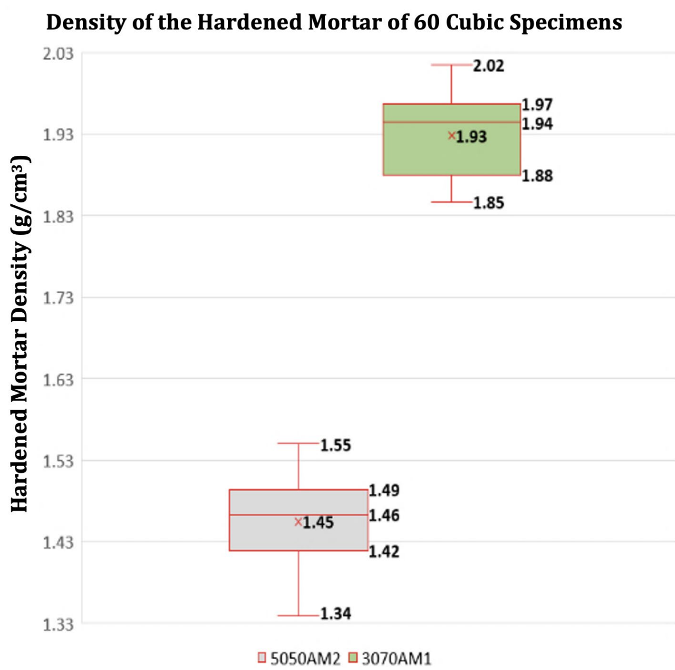

Figure 17. Densities of mortars made with the 5050AM2 and 3070AM. Source: Preparation by the authors.

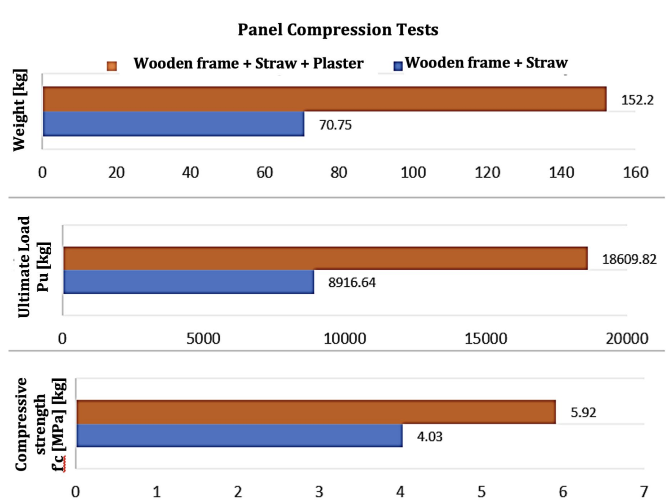

Figure 18. Results obtained from the compression test on panels with and without plaster. Source: Preparation by the authors.

higher than those obtained with the 5050AM2 mixture, as the average density is 1.93 g/cm^3. In this sense, the final mixture chosen as plaster in the panels with straw is the 5050AM2, which has a lower density.

The results of the weight, ultimate load, and compressive strength of the straw and wooden frame panels are shown in Figure 18. The weight of the panel with plaster is 152.20 kg, while without plaster, it is 70.75 kg, which indicates that the plaster adds more weight to the panel. As for the ultimate load, the panel with plaster has a value of 18609.82 kg, while without plaster, this value decreases to 8916.64 kg. Finally, a maximum compression strength of 5.93 MPa is obtained when the panel is plastered and a value of 4.03 MPa if it is not. Therefore, the plaster or coating mortar increases the ultimate load and provides greater strength to the panel.

CONCLUSIONS

After analyzing the results, it can be concluded that, on the one hand, using accelerator additives in lime-containing mixtures is beneficial, as a higher efficiency is demonstrated by using perlite as a fine aggregate. The low density of the perlite allows a greater amount of binder in the mixtures and, therefore, a greater amount of additive. In addition, it allows reducing the density of mortars by up to 24.87%, compared to those mortars where sand is used as fine aggregate.

Thus, it is found that mixtures made with perlite have better compressive strengths than those containing sand, given the high absorption capacity of perlite, which contributes to reducing lime setting times by absorbing kneading water quickly, unlike sand, which does not have this property.

The 5050AM2 mixture (50% lime, 50% cement, perlite, with additive) turned out to be the optimal one for the manufacture of a mortar, as it meets the minimum required strength of 6.89 MPa (according to the IRC 2018) to be used as a coating on straw walls. This mixture contains a greater amount of lime. It allows obtaining mortars with a compressive strength of 7.22 MPa after 28 days, with a density of 1.45 g/cm^3, lower than the characteristic density of conventional mortars.

In terms of the dosage of the 5050AM2 mixture (50% lime, 50% cement, additive, and perlite), for one cubic meter of low-density mortar to be used as a coating on straw walls, 205.71 kg of lime, 261.82 kg of cement, 552.50 kg of perlite, 371.72 kg or liters of water and, finally, 13.09 kg of additive are required.

In conclusion, the findings of this research support the suitability of the coating mortar made with the 5050AM2 mixture (50% lime, 50% cement, perlite, with additive). When applied on both sides of the panel, it protects and controls the humidity inside it and increases the ultimate load and compressive strength up to 47.91% and 68.07%, respectively.

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BIOCLIMATIC DESIGN OF MIDDLE HOUSING IN THE TIMES OF THE OIL BOOM IN TAMPICO, MEXICO (1912-1930)[1]

DISEÑO BIOCLIMÁTICO DE VIVIENDA MEDIA EN LA ÉPOCA DEL AUGE PETROLERO EN TAMPICO, MÉXICO (1912-1930)

PROJETO BIOCLIMÁTICO DE MORADIAS MÉDIAS DURANTE O BOOM DO PETRÓLEO EM TAMPICO, MÉXICO (1912-1930)

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RESUMEN

El presente trabajo tiene por objetivo determinar estrategias bioclimáticas adecuadas para el clima de Tampico y comprobar si fueron aplicadas en la vivienda media construida en la época del auge petrolero en la ciudad. Mediante la caracterización climática de Tampico y la revisión de recomendaciones realizadas por autores de arquitectura bioclimática, se establecen las estrategias aplicables al clima local. Se realiza un catálogo de viviendas de la época con características bioclimáticas, obteniéndose acceso a cinco. Mediante entrevistas a los usuarios, se buscó conocer su percepción sobre el confort interior y para profundizar, se estudiaron exhaustivamente las viviendas en cuanto a la existencia o no de estrategias bioclimáticas. Se concluye que dichas viviendas sí cuentan con estrategias bioclimáticas adecuadas para el clima y que eran las mismas que las utilizadas en las viviendas de la época de referencia (auge petrolero) y que han ayudado en la mejora del confort interior de los edificios. Utilizarlas actualmente ayudará a minorar el calentamiento interior, el uso excesivo de energías no renovables y los altos costos por consumo energético.

Palabras clave
arquitectura bioclimática, clima cálido-húmedo, vivienda, sistemas pasivos, flujo de viento.

ABSTRACT

This paper aims to determine bioclimatic strategies suitable for the climate of Tampico and to confirm whether they were applied in the middle housing built during the oil boom in the city. The strategies applicable to the local climate are established using a climatic characterization of Tampico and a review of the recommendations by bioclimatic architecture authors. A housing catalog of the time with bioclimatic characteristics is made, obtaining access to five. Users are interviewed to know their perception of indoor comfort, studying the housing in depth regarding the existence or not of bioclimatic strategies, concluding that they have climate-appropriate bioclimatic strategies, which are the same as those used in the houses of the time (oil boom), and that have helped to improve the indoor comfort of the buildings. Using them today will help reduce indoor heating, the excessive use of non-renewable energies, and the high energy consumption costs.

Keywords
bioclimatic architecture, hot-humid climate, housing, passive systems, wind flow.

RESUMO

Este artigo tem por objetivo determinar estratégias bioclimáticas adequadas ao clima de Tampico e verificar se elas foram aplicadas nas habitações de médio porte construídas durante o boom do petróleo na cidade. Por meio da caracterização climática de Tampico e da revisão das recomendações feitas por autores de arquitetura bioclimática, são estabelecidas as estratégias aplicáveis ao clima local. Elaborou-se um catálogo de residências da época com características bioclimáticas, obtendo-se acesso a cinco. Por meio de entrevistas com os usuários, buscou-se conhecer sua percepção em relação ao conforto interior e, para aprofundar o estudo das habitações, estudou-se exaustivamente a existência ou não de estratégias bioclimáticas. Conclui-se que essas residências possuem estratégias bioclimáticas adequadas ao clima, que são as mesmas utilizadas nas residências do período de referência (boom do petróleo) e que ajudaram a melhorar o conforto interno dos edifícios. Usá-las na atualidade ajudará a reduzir o aquecimento interno, o uso excessivo de energia não renovável e os altos custos decorrentes do consumo de energia.

Palavras-chave:
arquitetura bioclimática, clima quente-úmido, habitação, sistemas passivos, fluxo de vento.

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INTRODUCTION

At the beginning of the 20th century, the Mexican city of Tampico was experiencing an oil rush that led people from all over the world to come to the area needing housing (Bartorila & Loredo, 2017). These imported constructions added design proposals adapted to the climate and environmental conditions, even though they had been designed for different climatic situations (Spuna-Mújica, 2011). In this historical period, it was observed that the house had passive systems that could be reused and extrapolated for the design of current housing in Tampico, whose climate has similar characteristics to those of that time. This constitutes a finding that adds a new patrimonial dimension linked to the bioclimatic behavior of buildings with an intrinsic value as cultural heritage (Domínguez Ruiz & Rey Pérez, 2019).

Rubio-Bellido et al. (2015), with their study on housing in the historic hub of Cádiz in Spain, and Beltran-Fernandez et al. (2017), with their analysis of Frank Lloyd Wright's Jacobs I house, among others, have identified the bioclimatic contribution that historical housing currently provides. The results show that despite global warming and having been built when there were no resources to obtain comfort, they still work for the climates in which they are located.

It is commonplace to observe that the climate has ceased to be considered in the architectural design of housing (Van Hoof et al., 2010). In this case, Tampico has a hot-humid climate (Cruz-Rico et al., 2015), with temperatures and relative humidity of 25.7°C and 75%, respectively. This situation, coupled with the increase in temperatures due to global warming (Fraser et al., 2018), has led the locals to widely use air conditioning equipment (Morgan & Gómez-Azpeitia, 2018) to achieve comfort. In this regard, authors such as De Dear (2004), Olgyay (2004), and Givoni (1992) have stated that if climatic conditions were taken into account through passive design strategies in buildings, hygrothermal comfort could be achieved inside and outside.

In this regard, Olgyay (2004) and Givoni (1992), consolidated pioneers of bioclimatic architecture, have developed methods and instruments to identify appropriate strategies for designing a building's urban and interior space, respectively, considering the climatic conditions of the place. Therefore, this research is based on these two complementary and parallel consolidated methods to analyze case studies in Tampico, adapting the phases developed by the authors to this research.

As for comfort, Monroy (2001)points out that for a building or public space to be comfortable all year round, it would be enough that it behaves appropriately on a typical winter and summer day. This reference has been taken as part of the research hypotheses, defining Tampico's extreme summer and winter conditions and extrapolating the intermediate stages to the rest of the year, given the low annual variation of local climatic conditions.

According to bioclimatic adaptation studies, the most effective strategies for a hot-humid climate, as is the case in Tampico, include solar protection and natural ventilation (Ahmed et al., 2021). Solar protection is crucial to reduce the cooling load in indoor spaces, while natural ventilation, as researched by Velasco-Roldán (2011), improves air movement and contributes to hygrothermal comfort.

On the other hand, it is essential to consider both the effectiveness of these systems in indoor and outdoor comfort and the reduction of indoor temperature and energy saving, as has been demonstrated by Hu et al. (2023) and Givoni (2011). The study by Elaouzy and Fadar (2023) looks closer at bioclimatic adaptation strategies for hot-humid climates, providing valuable information on how these strategies can be effectively applied in contexts such as Tampico. On the other hand, Serra Florensa and Coch Roura (1995) offer a detailed view of using natural ventilation systems as part of environmental control or passive systems, indicating their limits and hygrothermal comfort.

Rosas-Lusett et al. (2020) also conducted a study highlighting urban design strategies to achieve hygrothermal comfort in outdoor spaces. Among the recommendations to favor an adequate wind flow indoors is the appropriate integration of vegetation and its relationship with the facades and the separation between houses, among other suggestions. These strategies are fundamental to identifying and studying appropriate bioclimatic strategies, adapted to both climate and physical conditions, considering the geography, orography, and urban morphology (Manzano-Agugliaro et al., 2015), as well as to the cultural reality and local ways of life in the city of Tampico.

These investigations are framed within the connection between the development of life and the climatic conditions of a place for housing design, as highlighted by authors such as Gaytan-

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Ortiz (2019) and Szokolay (1986). It is essential to consider these approaches to ensure a housing design that adapts effectively to climatic conditions and the historical-anthropological constraints of the cultural context (López de Asiain, 2001). Therefore, and given that the objective of this research is the identification and study of the bioclimatic strategies and passive systems used in the middle housing of the oil boom in Tampico, these will be identified, and the elements and/or systems will be recognized for each of the homes, thus analyzing their operation.

METHODOLOGY

The methodology to identify the bioclimatic systems and strategies in the homes of the oil boom in Tampico was based on extensive field research. Firstly, a climatic characterization of Tampico was made based on its hot-humid climate, with two distinguishable climatic periods (warmer and cooler months), using information from the SMN (1981-2010) in the EPW archive. Using a psycho-physiological adaptive model (Auliciems, 1981), the neutral temperature (Tn) and the limits of the comfort zone were calculated (Szokolay, 2014). Subsequently, using the psychrometric graphs of Givoni (interiors) and Olgyay (exteriors), the strategies recommended for the type of climate were identified in two aspects: characteristics of the set and passive architectural design of the housing. This analysis used programs such as Photoshop, WRPlot, Climate-consultant, and 2D-Sun Path by Andrew Marsh.

The sample selection for this research was non-probabilistic, as it depended on obtaining access permissions. The study area covered the Águila and Altavista neighborhoods, where a catalog of twenty-seven homes from the time of the oil boom was made, of which five were identified as case studies on potentially having a bioclimatic design. These homes were analyzed in depth through planimetric surveys, photographs, and interviews with users to find out the origin, the daily activities of the occupants, and the personal perception of thermal comfort, in addition to determining the current state compared to the original.

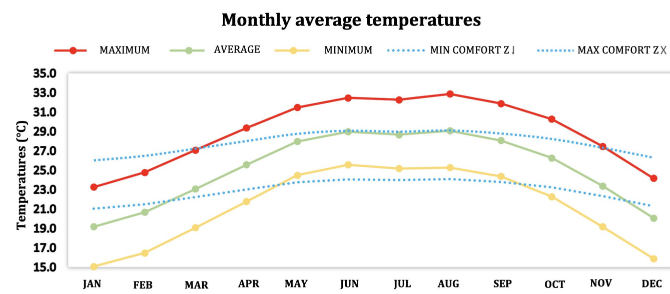
All this information was integrated into a typological file to identify the bioclimatic strategies and systems used, corroborating their proper operation when facing the city's climate. In addition, a review of strategies was carried out, observing that they were effectively used in the design of the average house built during the oil boom, identifying the passive systems used, and defining and characterizing them.

RESULTS AND DISCUSSION

CLIMATIC CHARACTERIZATION AND COMFORT ZONE

Temperature

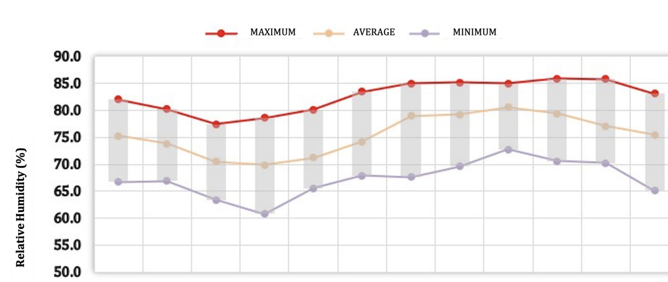
The average temperature in Tampico is 25.7°C. Graph 1 shows that the warmest months are from March to November, with average temperatures between 23 and 30 °C. In addition, the thermal oscillation in the two periods is between 7 and 8°C, and their average maximum is up to 33°C. The cooler months are from December to February, with temperatures from 15 to 20°C.



Graph 1. Monthly temperatures. Source: Preparation by the authors based on SMN data, Tampico Climatological Station, CONAGUA, 1981-2010.

Relative humidity

The city of Tampico, Mexico, is characterized by its environment, surrounded by bodies of water and its proximity to the coast of the Gulf of Mexico. This geographical location significantly influences the area's relative humidity, which is affected by the condensation of water vapor and high temperatures. Graph 2 shows that the months with the highest humidity extend from June to November, reaching 85% relative humidity. On the other hand, the months with the lowest humidity comprise the period from December to May, with values of up to 60%. Interestingly, February, March, and April are characterized by lower humidity coinciding with a higher wind speed, while the months with higher humidity, from July to November, coincide with a lower wind speed.



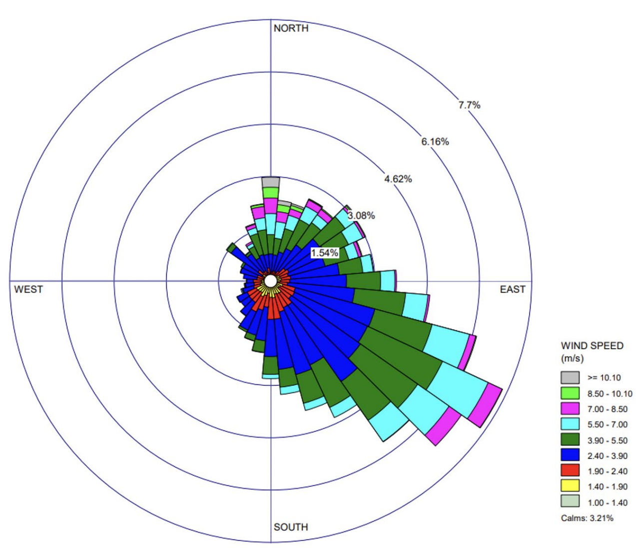
Graph 2. Monthly relative humidity. Source: Preparation by the authors based on SMN data, Tampico Climatological Station, CONAGUA, 1981-2010.

Solar radiation

In Tampico, the solar radiation is highest during the warmer months, with more sunny days and hours. During the summer solstice, the right angle of the sun at noon reaches 83.75°, indicating more direct exposure to the sun during this time of the year.

Winds

The average wind speed in Tampico is around 4.17 m/s, with the fastest speed being in February, March, and April. On the contrary, the month with the lowest speed is in August. The prevailing wind direction is usually from the southeast, with seasonal changes during the year. Thus, in June, July, and August, there is a higher presence of softer southeast winds (Graph 3), while in December and January, the north winds predominate, and in March, April, and May, the predominant direction is from the east and with a higher speed.



Graph 3. Wind rose of Tampico, Tamaulipas, 2020. Source: Preparation by the authors based on SMN data, Tampico Climatological Station, CONAGUA, 2020

Solar geometry

Tampico has a clear pattern in the length of days over the year, with the longest day in June (13 hours, 30 minutes) and the shortest in December (10 hours, 46 minutes). Figure 1 shows the relationship of the sun with the daily temperatures per month.

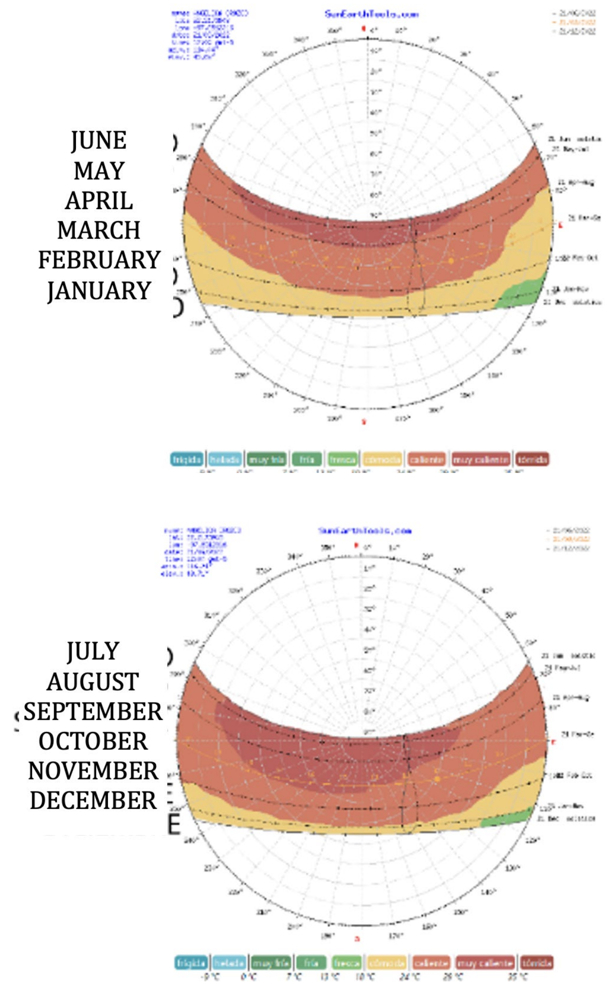


Figure 1. Stereographic solar graph + Hourly temperature for the months of the year in Tampico. Source: Prepared by the authors with data from the Tampico weather station, SMN

Comfort zones and neutral temperature

The analysis distinguishes two significant climatic periods in Tampico: the cooler months (December to February) and the warmest months (March to November). On the other hand, the comfort zones are determined using an adaptive model.

In another aspect, the neutral temperature (Tn) is calculated by a psycho-physiological thermal perception model proposed by Auliciems (1981), whose formula is as follows: Tn=(Tm*0.31) +17.60, where (Tm) is the average temperature of each month (Tm) obtained from the climatic characterization. The comfort zone is established based on the limits proposed by Szokolay, with 90% acceptance, +2.5°C upper limit, and -2.5 lower limit.

DETERMINATION OF BIOCLIMATIC STRATEGIES FOR THE CITY OF TAMPICO, ACCORDING TO GIVONI AND OLGYAY

From the climatic characterization, the data of a typical day of each month of 2020 were obtained, using the maximum and minimum average temperatures as a guide. These data were plotted in the bioclimatic diagrams of Givoni (interior) and Olgyay (exterior), following what was indicated in Ribeiro et al. (2015).

The Givoni diagram (Figure 2) shows that solar heating and inertia in winter are recommended in the schedules outside the comfort zones for December, January, and February. On the other hand, March, April, September, October, and November are located within the comfort zone or in the area whose recommended strategy is ventilation. May, June, July, and August are mainly outside the comfort zone and within the A/C strategy.

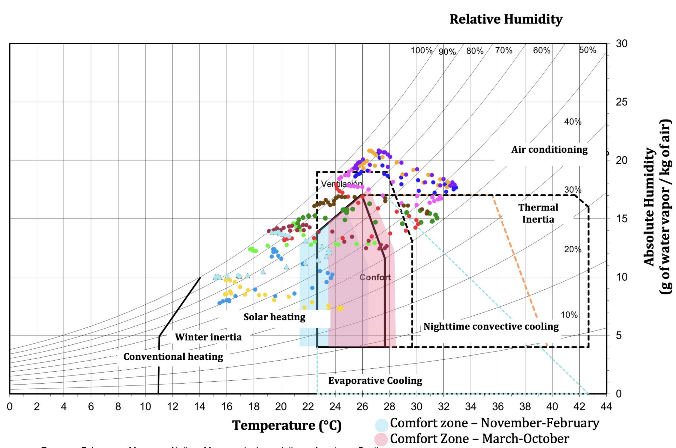


Figure 2. Psychrometric diagram of Givoni. Source: Preparation by the authors.

As for the Olgyay graph (Figure 3), it is observed that most months of the year are within the ventilation strategy zone, which suggests that air movement is an effective strategy in these months. However, August exceeds the limits towards heat, which indicates a lower effect of the ventilation strategy and the need to consider other strategies, such as radiation, to counteract the excess heat in this month with lower wind speed.

The standout bioclimatic strategy, both indoors and outdoors, is air movement. In addition, the need to consider solar radiation for cooler months is indicated, as the sun regulates high indoor humidity levels.

This analysis of strategies is complemented by Olgyay's proposal (2004) for architectural design in hot-humid regions, focusing on two fundamental areas: the characteristics of the set and immediate environment and the passive architectural design of housing.

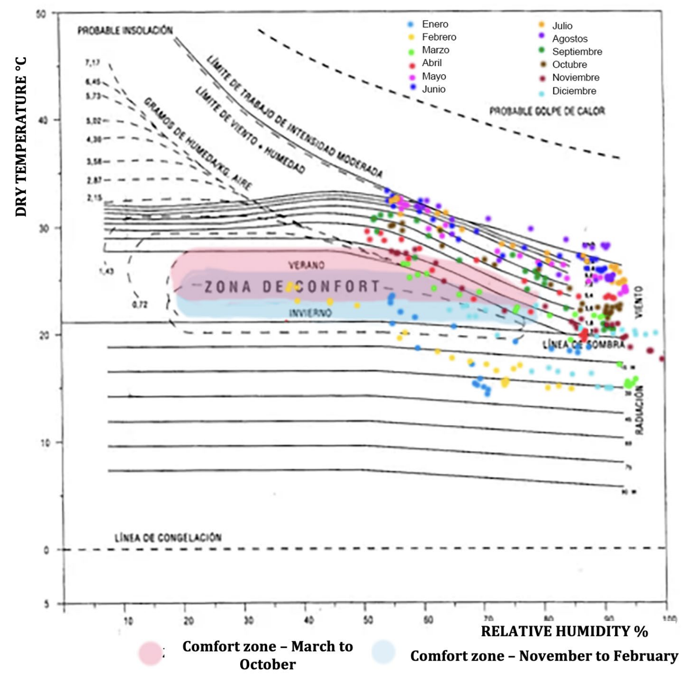


Figure 3. Olgyay's Graph. Source: Preparation by the authors.

Characteristics of the set

- Locations at high altitudes to capture the most wind.
- Houses separated from the surrounding areas to take advantage of air movements and direct it more easily indoors.
- High-branched trees located to the west provide shading without hindering air movement.

Passive architectural design of housing

- Prioritize the airflow inside using interior spaces connected to each other.
- The shape of the building is slightly elongated on the east-west axis, L-shaped, U-shaped, or with a central courtyard to favor the passage of winds and the movement of air inside. Attics, ceilings, and space between natural terrain and the interior floor will prevent heat from entering the living space. These spaces should be ventilated in summer and their ventilation controlled in winter. Interior heights greater than 2.60 mts so that the hot air rises and does not remain at the height of the users.
- Combinations of size and location in openings and windows that allow favoring cross ventilation, conserving or pushing the wind to obtain better results with the necessary ventilation most of the year. Lattices, blinds, and meshes reduce

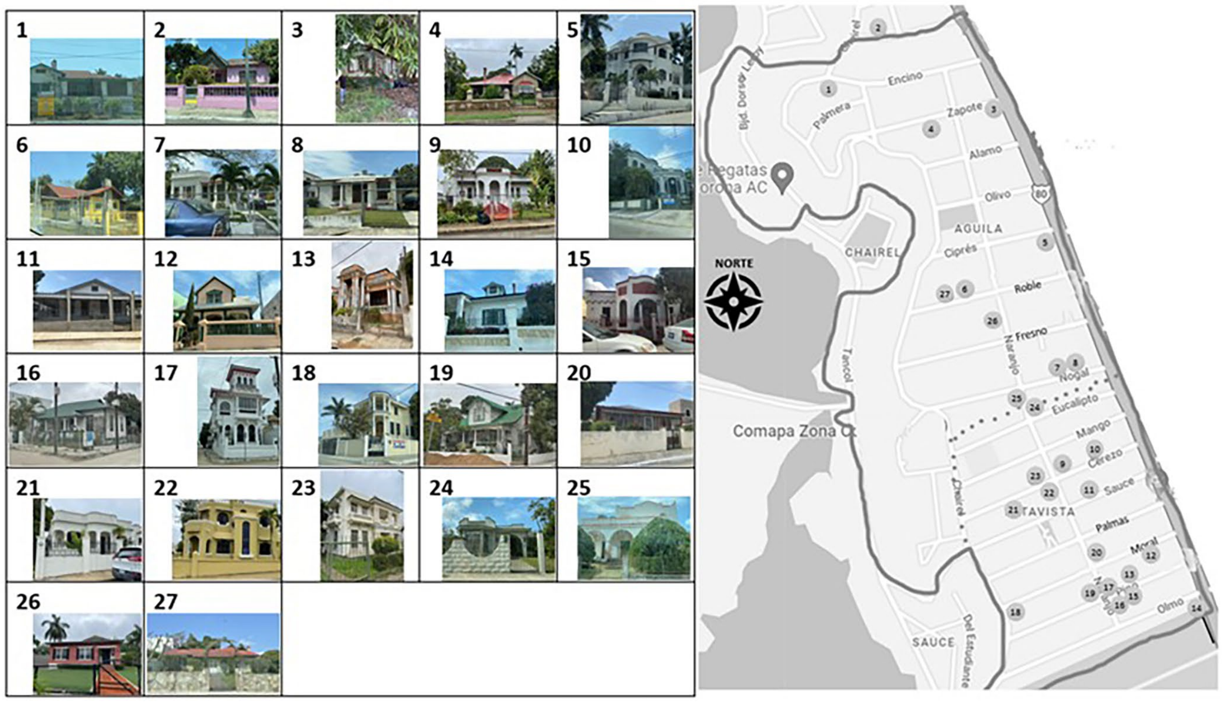


Figure 4. Total catalog of selected homes in Aguila and Altavista neighborhoods. Source: Preparation by the authors

radiation and allow air to flow into the spaces.

- Solar protection elements to the east and west. Eaves or slab extensions that help with shading. Porches, terraces, or balconies that keep the sun away from the building and allow taking advantage of the wind in the area.
- The most suitable orientation is north-south.
- Light colors that ensure reflectance indoors and outdoors.

CASE STUDIES AND ANALYSIS

For the selection of the study homes, a catalog of twenty-seven homes was made using the following criteria (Figure 4):

1. Houses built during the study period (1912-1930).
2. Currently inhabited dwellings.
3. Houses in very good condition.
4. Homes that have not undergone significant modifications.
5. Houses that are naturally ventilated in most of their spaces

Access was requested to the twenty-seven homes, and permission was obtained for only five, confirming that they met all the selection criteria. The dwellings that constitute the sample of case studies of the research are the following (Figure 5):

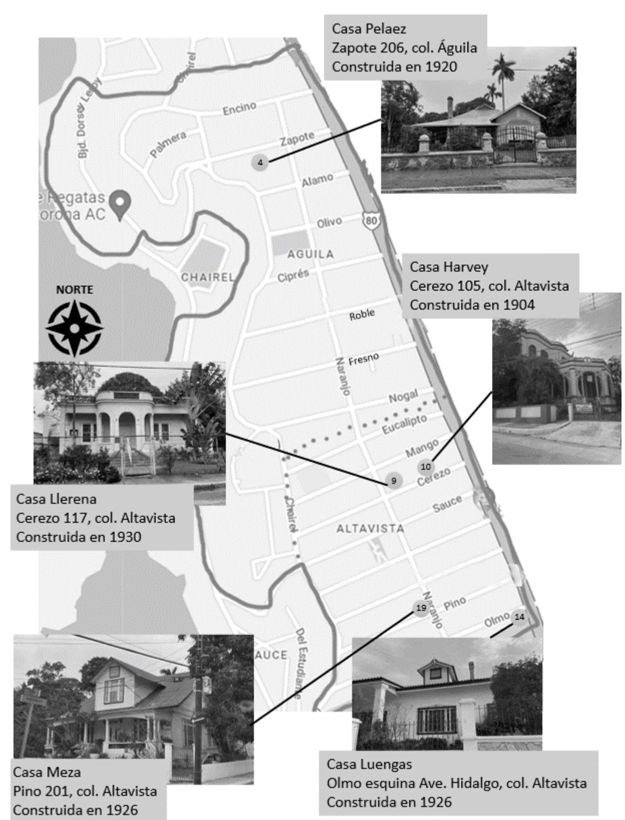


Figure 5. Location of case study housing. Source: Preparation by the authors

The detail of the houses is explained below:

1. Casa Harvey, located at 105 Cerezo Street, Altavista neighborhood. Built in 1914 and restored in 2004, it has had several owners. It is inhabited by a young couple with a child (Figure 6).

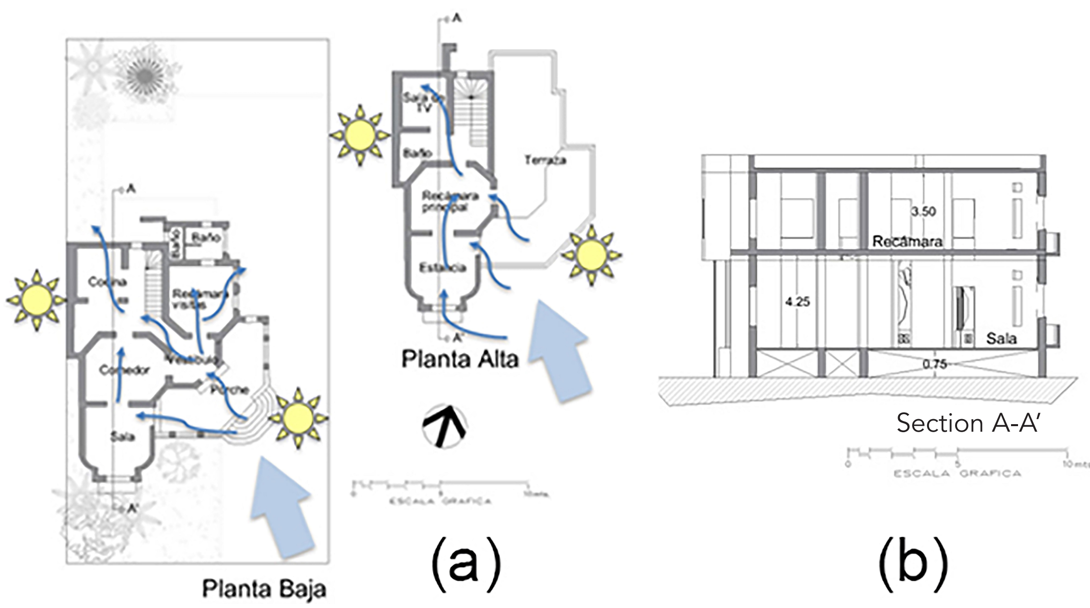
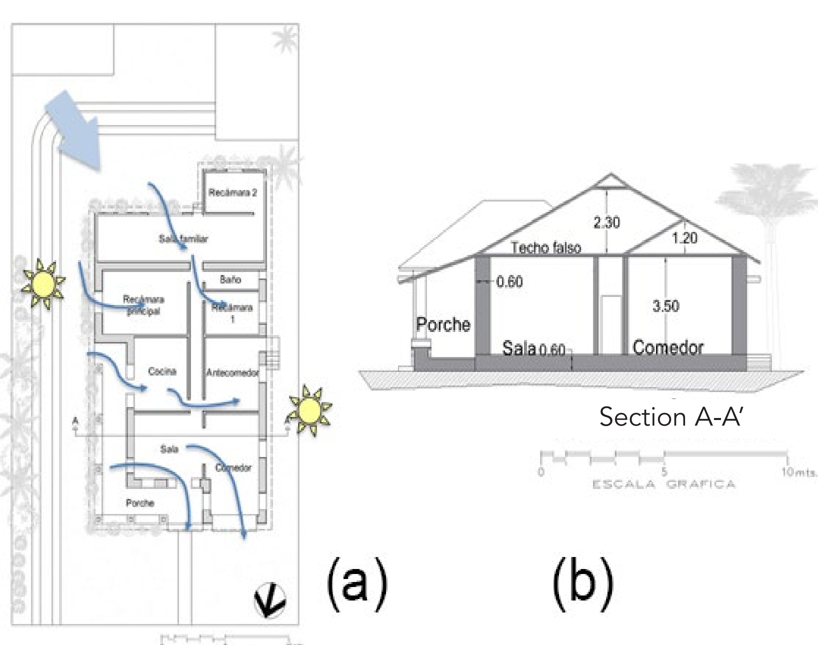


Figure 6. (a) Architectural floorplans (b) Cross section. Source. Preparation by the authors

2. Casa Peláez, located at Calle Zapote 206, Águila neighborhood. Built in the 1920's by the company El Águila. It has belonged to the current owner since 1940 and is inhabited by an older adult and a young person (Figure 7).



.Figure 7. (a) Architectural floorplans (b) Cross section. Source. Preparation by the authors.

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3. Casa Meza, located at 201 Pino Street, Altavista neighborhood. Built in 1926. It has belonged to the current owner since 1930 and is inhabited by a couple of adults (Figure 8).

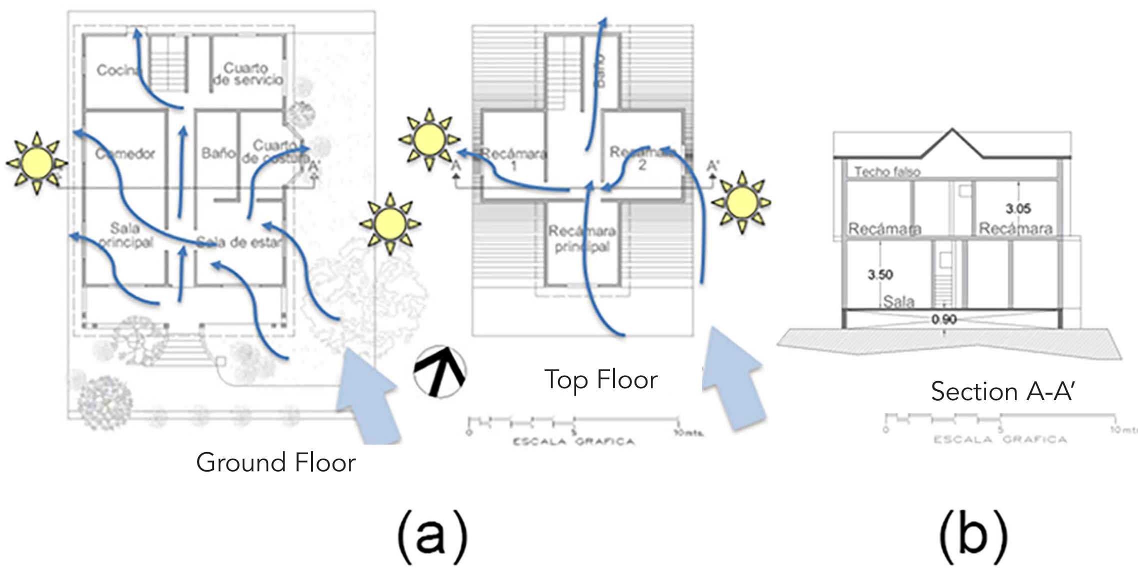


Figure 8. (a) Architectural floorplans (b) Cross section. Source. Preparation by the authors

4. Casa Llerena is located at 117 Cerezo Street in the Altavista neighborhood. It was built in 1929. It has been owned by the current owners since 1936 and is inhabited by one adult (Figure 9).

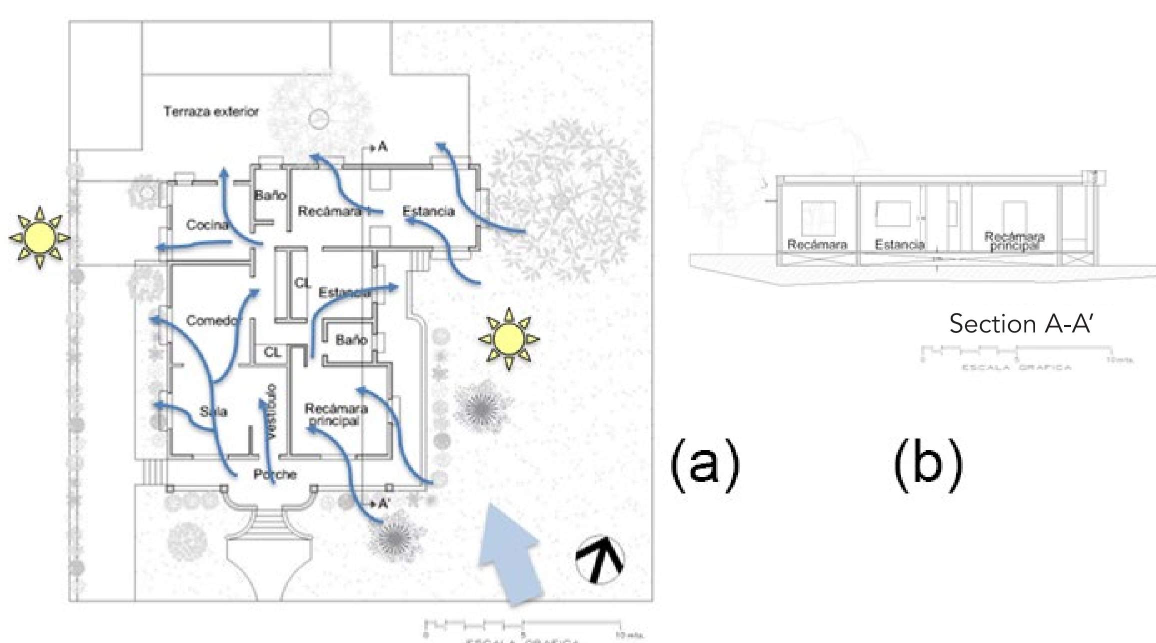


Figure 9. (a) Architectural floorplans (b) Cross section. Source. Preparation by the authors

5. Casa Luengas in Avenida Hidalgo, in the Altavista neighborhood. It was built in 1926. It has been owned by the current owners since 1938 and is inhabited by an older adult and a young person (Figure 10).

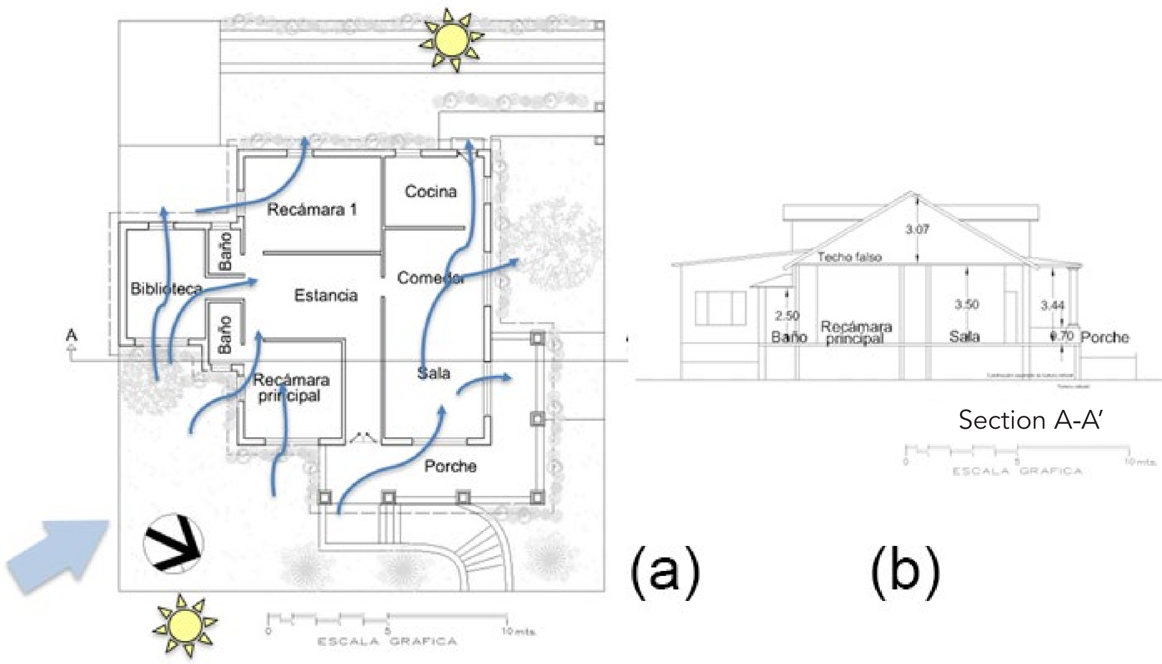


Figure 10. (a) Architectural floorplans (b) Cross section. Source. Preparation by the authors

Characteristics and immediate surroundings of the set

Considering the characteristics of the immediate surroundings of Tampico's Águila and Altavista neighborhoods, it is observed that these areas have an average altitude of 20 masl, with north-south oriented terrain and an area of 500-1000m². Sufficient vegetation favors the shading of the facades and the surrounding environment, contributing to the proper bioclimatic operation and the interior comfort of the houses. The same happens with the layout towards the center of the houses, as this allows an optimal wind flow, which is beneficial for thermal comfort inside.

These conditions provide a favorable environment for the effective implementation of bioclimatic and sustainable strategies, providing comfort and energy efficiency for the inhabitants. In new urbanizations, it is recommended to prioritize these favorable conditions, including sufficient vegetation for shading, open spaces, and efficient distribution of housing to favor air movement. In those cases where these conditions cannot be replicated, complementary recommendations should be considered, such as shading strategies and landscape design, to ensure indoor comfort and the effective operation of the bioclimatic strategies.

ARCHITECTURAL DESIGN OF THE HOUSES

The study's objective was to identify the bioclimatic strategies and/or systems incorporated in the architectural design of each of the study homes, considering the bioclimatic strategies recommended for the climate of the city of Tampico. This process involved identifying and describing the bioclimatic strategies and systems identified in the studied homes. All this is briefly summarized in Table 1.

When comparing the findings of this study, it can be observed that the case study homes have incorporated, in a generalized way, design criteria aligned with the bioclimatic strategies defined in the research. These strategies represent elements and systems that have endured over time, thanks to their good performance in terms of occupant comfort.

As for the housing design, case studies with a semi-compact shape are observed, which is not recommended. However, cross ventilation and air movement inside are favored by having porosity characteristics (openings in all facades), interior openings, high mezzanines, and ventilated double slabs.

The strategies are generally met with the passive systems from Table 2.

Table 1. Elements identified for ventilation, air movement, and shading strategies. Source: Preparation by the authors.

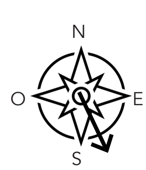
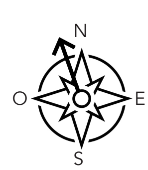
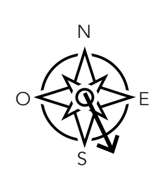
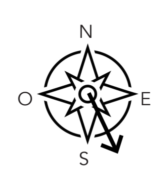
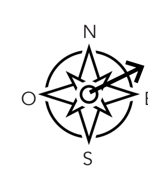
Bioclimatic strategies for the climate of Tampico	Casa Harvey	Casa Peláez	Casa Meza	Casa Llerena	Casa Luengas
Open interior spaces. VENTILATION	Cross ventilation in bedrooms and social area. Low fences with ironworks favor the passage of the wind to the site.	Interior spaces with facing accesses favoring wind flow. Low fences with ironworks favor the passage of the wind to the site.	Interior spaces with facing accesses favoring wind flow. Very low fences with ironworks favor the wind's passage to the site.	Large spaces with two windows or more favoring cross ventilation. The very low fence favors the passage of the wind to the site.	Large spaces with two windows favoring cross ventilation. Mesh fence favoring the passage of the wind to the site.
Shape AIR MOVEMENT	Semi-compact and porous construction. The ratio is 1:1.30, raised +0.75m from the floor—3.50 m high mezzanines.	It has elongated north-south construction. The ratio is 1:1.80, raised +0.45m from the floor. It has an attic, a false ceiling, and openings to get the hot air out—3.50 m high mezzanines.	Semi-compact and porous construction. The ratio is 1:1.50, raised +0.90m from the floor. It has an attic, false ceiling, and openings to get hot air out. The apartment is separated from the natural terrain and has openings on the perimeter, with mezzanines that are 3.50 m high.	Semi-compact and porous construction. The ratio is 1:1.25, raised +0.90m from the floor—3.50 m high mezzanines.	Semi-compact and porous construction. The ratio is 1:1.20, raised +0.30m from the floor. It has an attic, false ceiling, and openings to get hot air out—3.50 m high mezzanines.
Openings and windows VENTILATION	Openings percentage: Southeast 13.13%; Northwest 18.91%; East-north: 12.58%; West-south: 9.29%	Openings percentage: Southeast 35.16%; Northwest 27.41%; East-north: 15.73%; West-south: 15.09%	Openings percentage: Southeast 29.42%; Northwest 12.84%; East-north: 22.44%; West-south: 17.10% *The roof was not considered.	Openings percentage: Southeast 17.11%; Northwest 13.25%; East-north: 13.38%; West-south: 15.85%	Openings percentage: Southeast 8%; Northwest: 18.21%; East-north: 21.44%; West-south: 12.21%
Solar protection elements SHADING	Roofed southeast-facing porch that is 3.15m wide by 10.8m.	40 cm wide perimeter eaves. Roofed Northwest and East-North facing L-shaped porch, 3.5m average width.	40 cm wide perimeter eaves. Roofed southeast-facing porch, 1.74mts wide.	Wide eaves with 50 cm windows. "L"-shaped roofed Southeast and East-North facing porch, 1.6m average width	40 cm wide perimeter eaves. Covered "L" shaped West facing porch, 2 m average width.
Orientation VENTILATION AND LESS PERPENDICULAR RADIATION	 South 23°East	 North 14°West	 South 26°East	 South 23°East	 East 22° North
Reflective colors inside and outside. ENSURING REFLECTANCE	Light gray paint outdoors, white indoors. White roof.	Apparent light-yellow stone finish outdoors, beige indoors. Red sloping roof.	White paint on the exterior, white on the interior. Green sloping roof.	Light gray paint outdoors, white indoors. White roof.	White paint outdoors, beige indoors. Green sloping roof.

Table 2. Elements and/or systems identified. Source: Preparation by the authors.

Recommended strategies for the city's climate	Systems identified in the studied housing
Open interior spaces to favor ventilation.	Spaces with interior openings facing each other. Doors with openings that allow wind to pass through. Cross ventilation in bedrooms and social spaces.
Open outdoor spaces to favor ventilation.	Use of low fences or meshes to favor the passage of the wind inside the site.
Shapes that allow reducing the radiation inside	Housing with attics and double ceilings with ventilation to get the hot air out. Houses on the level of the natural terrain. In a house separated from the natural terrain, there are openings for air movement and humidity reduction.
Shapes that favor air movement	High ceilings favor the air movement and allow the hot air to rise and not be at the user level.
Openings and windows that favor ventilation with shading systems and decrease indoor radiation	Large clearings on the south and north facades. Perimeter eaves on roofs. Individual eaves by window. South, east, and west-facing porches.
Solar protection elements that they prevent radiation inside the openings	Porches that prevent radiation from coming inside. Eaves by windows and perimeters.
Orientation that favors ventilation.	Large-sized windows face the prevailing winds, which may not cause high air pressures but allow the wind to pass inside.
Reflective colors inside and outside to decrease heat transfer.	In general, light colors are observed on indoor and outdoor walls. On roofs, some houses are white, two are green, and one is red.
Vegetation within the property to favor shading	The houses have medium to large-sized vegetation—trees placed on the east and west facades, which helps with shading.

After analyzing the results, it is demonstrated that the passive bioclimatic strategies defined in the Givoni psychrometric diagram are applied in the homes under study in their original design. Likewise, the most crucial strategy in the interior is natural ventilation, especially in the warm months, corroborating the conclusions of Velasco-Roldán (2011). The observation of simple design systems in these homes, such as large windows facing windward and interior doors with upper windows, favor cross-ventilation and the passage of air between spaces. These systems can be extrapolated to current housing designs, as they can significantly improve indoor hygrothermal comfort.

Regarding the strategies defined by the Olgyay outdoor graph and corroborated by the studies of Roses-Lusett et al. (2020), it can be concluded that they are suitable depending on the greater comfort in the immediate surroundings of the buildings, which can positively influence the air temperature before entering the house, also improving indoor comfort.

Finally, it is shown that the follow-up of the criteria defined by The New York Times (2014) and Lopez de Asiain (2001) regarding the methodological process and strategic approach of analysis of the physical and cultural-anthropological context has produced significant results that confirm that the homes studied and built during the oil boom in Tampico can be an important reference to improve the bioclimatic design of current housing in the area, in addition to standing out as a cultural and environmental heritage that deserves recognition (Domínguez Ruiz & Rey Pérez, 2019).

CONCLUSIONS

This study highlights the importance of housing architecture built during the oil boom in Tampico, as it is evident that the fact of having locally adapted bioclimatic strategies and systems manages to provide better and adequate comfort conditions to the houses (Espuna-Mújica, 2011). Although these original designs were imported from other contexts, they could be adapted to the local climatic context, demonstrating that the bioclimatic strategies were necessary and potentially usable for Tampico.

These systems characterized both generically in the studies of Serra Florensa and Coch Roura (1995) and specifically in those of Manzano-Agugliaro et al. (2015), have been validated as suitable to face the hot-humid climate. Likewise, the initial expectations about the city's historical housing contribution to a specific climate are confirmed, which could be critical for the current housing being built in the same city. These contributions should be studied and quantified in their extrapolation to the current housing in Tampico in future research.

It is concluded that, even though these houses, despite their aesthetic-historical-constructive interest, have not been classified as cultural heritage, they can make a significant contribution in environmental terms and bioclimatic behavior, so they could be considered environmental heritage, according to the proposals of authors such as King (2017). However, this research does not allow quantitatively determining the potential for comfort improvements of the studied designs. In this sense, this work can be considered the first part of more comprehensive research, where it has been possible to identify the bioclimatic strategies and systems used for the architectural design of housing. In this way, to continue this study, it will be necessary to make measurements and/or simulations of this behavior to check the effectiveness of housing comfort and thus know accurately the benefits of implementing the strategies and systems presented in this research in the current design.

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